

# Thermal resistance of the contact between the thermofoil heater and the TPG substrate

Cary Kendziora, Mauro Marinelli, Mark Ruschman

April 2, 05

DRAFT

## Summary

The purpose of the Heater / Epoxy Test is to obtain a better understanding of the thermal resistance from the heater to the substrate. This measurement is part of the design research and development of the substrate temperature control system for the BTeV Pixel Detector [1]. The substrate is a 0.38mm thick thermal pyrolytic graphite (TPG) layer. To control the substrate temperature it was planned to use heaters (4 per substrate) for thermal stability; the expected total maximum power is 50W and the effective area of each heater is 11.6 cm<sup>2</sup> (1.8 in<sup>2</sup>), so the power density is 1.1 W/cm<sup>2</sup>. The temperature sensitive resistance of the heating conductor used in the present apparatus allows measuring the temperature of the heating conductor itself. This note describes the methods used to attach the thermofoil heaters to the substrate and to measure the relative thermal resistances. Two tests, using different TPG substrates, have been done to verify the reproducibility of the heater attaching procedure. The first test measured four heaters directly attached on the TPG and other four heaters attached on the carbon fiber layer covering the TPG. The thermal contact of three out of four heaters attached directly on the TPG was good; only one heater out of the four heaters attached over the carbon fiber layer had a good contact. The second test was repeated attaching four heaters directly on another TPG substrate: all the four heaters showed a good contact.

## 1. Heaters and RTD

A standard thermofoil Minco heater (Fig.1) model HK5578 with Kapton insulation is used for these measurements. The electrical resistance of the heating element (nickel-iron NiFe heater conductor) is temperature dependent

$$\frac{R}{R_o} = 1 + \alpha T + \beta T^2 \quad (1)$$

where  $\alpha = 4.5309 \cdot 10^{-3} \text{ C}^{-1}$ ,  $\beta = 6.2647 \cdot 10^{-6} \text{ C}^{-2}$   
 $R_o$  is the resistance at 0 C and  $T$  is the temperature in degrees centigrade. The  $R_o$  of each heater has been measured in advance by the four wires method. Table 1 lists the ones used for the first test.

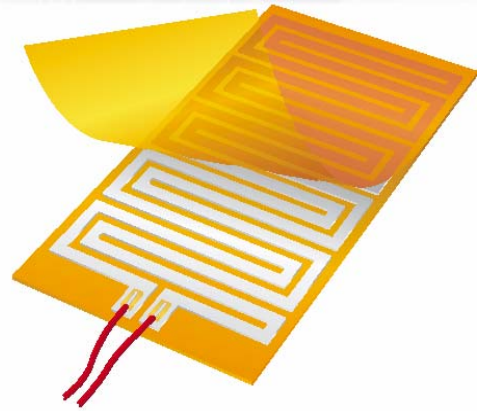


Table 1

Heater	Resistance $R_o$ @ 0 C
#	$\Omega$
1	5.371
2	5.223
3	5.315
4	5.274
5	5.427
6	5.480
7	5.384
8	5.402

Fig.1 Heater element Minco model HK5578. The overall size is 0.75 x 0.75 in<sup>2</sup> and the effective area, necessary to calculate the power density, is 0.48 in<sup>2</sup> = 3.1cm<sup>2</sup>. The electrical resistance at 0 C of this heater model is 5.4  $\Omega \pm 10\%$

We obtain the temperature of the heating element by equation (1). The resistance of the heaters installed on the first test substrates is not measured by the four wires method, because of the lack of feed through pins. All of the existing pins have been used for the 8 heaters and the 20 RTDs that are installed in the present setup. There are two wires identical to the wires used to feed the heaters and shorted at the end near the heaters. These wires follow the same path, as other heater wires, from the power supply to the heaters. The resistance of each heater is obtained by subtracting the resistance of these two wires ( $2.05 \Omega$ ) from the total heater circuit, measured at the power supply output pins. We will show later that this is a sufficient method to prove whether the thermal contact between the heater and the substrate is good or not.

For the same reason, the RTD resistances are calculated by measuring the complete RTD circuit and subtracting the resistance of another pair of wires of the same type as used on the RTDs. Note that an error of  $0.1 \Omega$  on the resistance of the  $100 \Omega$  (@  $0^\circ\text{C}$ ) RTD correspond to a temperature error of  $0.25^\circ\text{C}$ .

## 2. First Test Apparatus

There are two TPG substrates encapsulated with carbon fiber (CF) and installed on a copper plate. Figure 3 defines the heater and RTD labels and the glue used to attach each heater to the substrate. Figure 4a shows a picture of the two substrates installed on the copper plate. The substrate in the top part of the figure has the four heaters (H1-H4) attached over the CF and the other substrate in the bottom part of the illustration has the four heaters (H5-H8) attached directly on the TPG but under the CF. Figures 4b and 4c illustrate the difference in the layers between the heaters mounted on top of the Carbon Fiber and heaters sandwiched between the Carbon Fiber. Figure 5 shows a detail of the substrate with the heaters on the surface of the CF. The copper plate is thermally connected with the head of a cryocooler and installed in a vacuum vessel (Figure 6). It is possible to control the temperature of the cryocooler head.

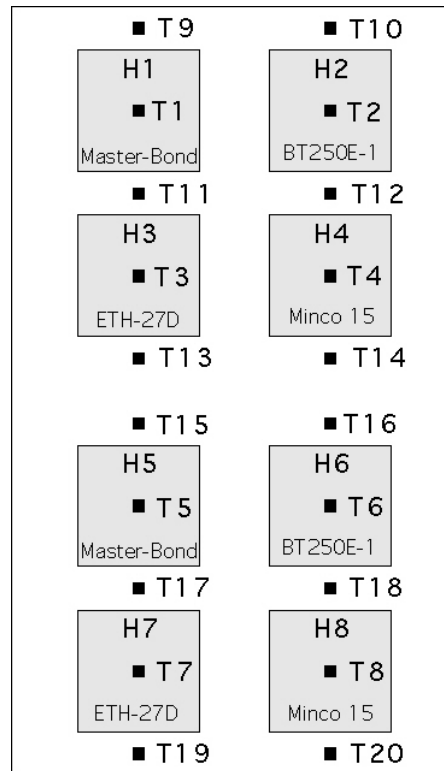


Fig.3 - Heater and thermometer positions on the TPG substrates. The **H1-H4** heaters are glued **over the CF** and the **H5-H8** heaters are glued on the TPG **below the CF**. The glue type is marked on each heater.

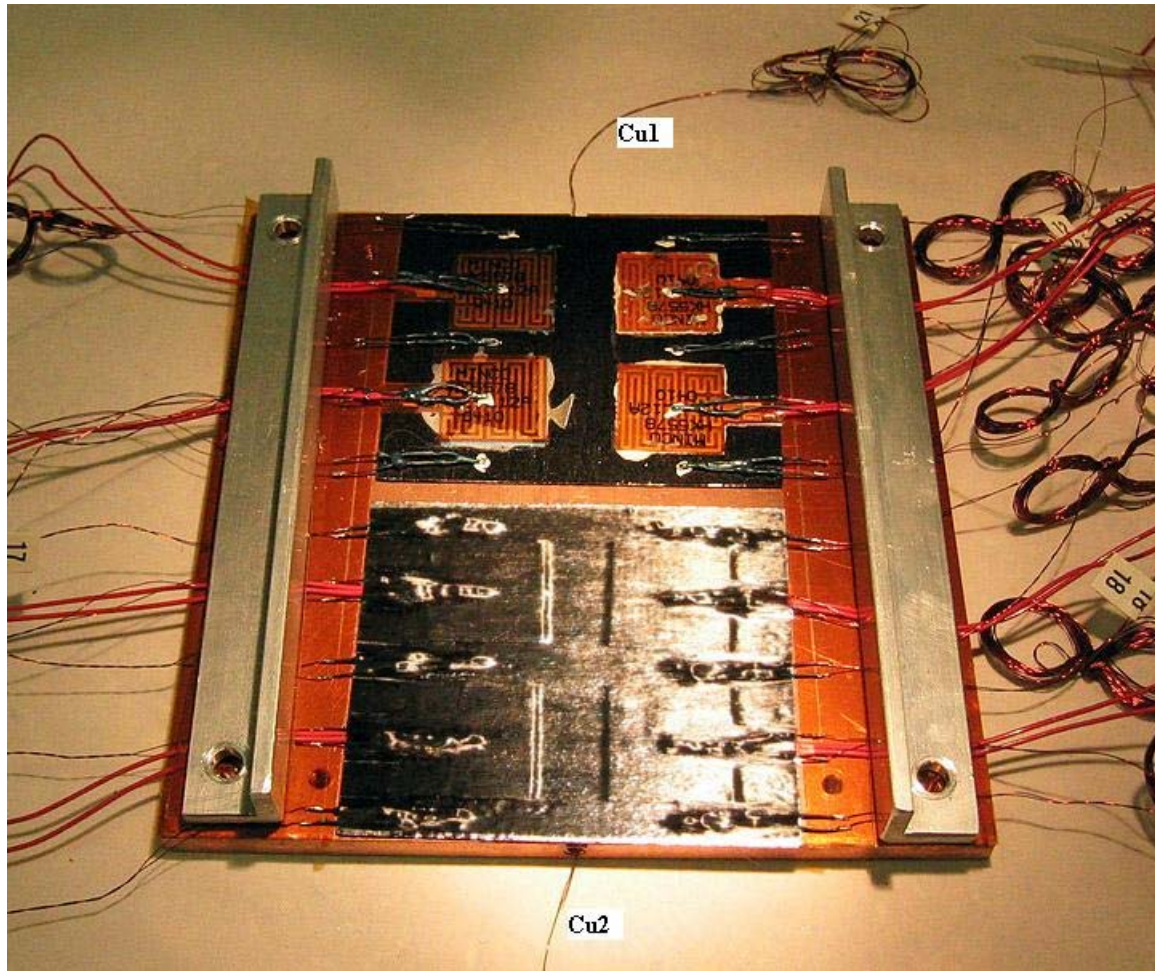


Fig. 4a - The substrate in the top part of the figure has the four heaters (H1-H4) attached over the CF and the other substrate in the bottom part of the figure has the four heaters (H5-H8) attached directly on the TPG but under the CF. The area of each substrate is  $3'' \times 2.25'' = 43.5 \text{ cm}^2$ . The thermometers  $\text{Cu}_1$  and  $\text{Cu}_2$  are installed at the center of the two shorter sides of the copper plate.

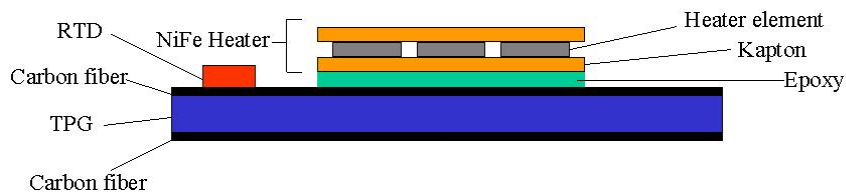


Fig. 4b – Layers in Heater Test with Heater on Top of the Carbon Fiber (not to scale). The figure shows the RTD attached on the TPG substrate near the heater left side, another RTD (not shown) is symmetrically attached near the heater right side and one is attached on the heater top.

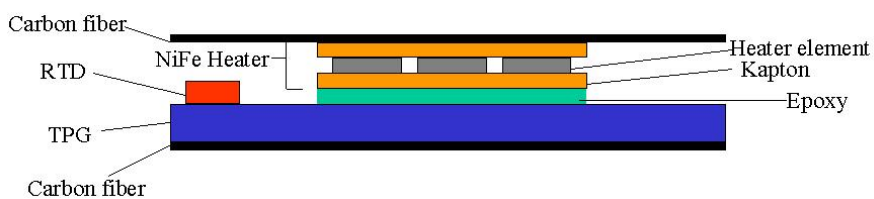


Fig 4c - Layers in Heater Test with Heater Sandwiched between the Carbon Fiber and TPG (not to scale). There are two RTDs attached on the TPG substrate near the heater (only one is shown). The carbon fiber layer covers these two RTDs and the one (not shown) attached to the top of the heater.

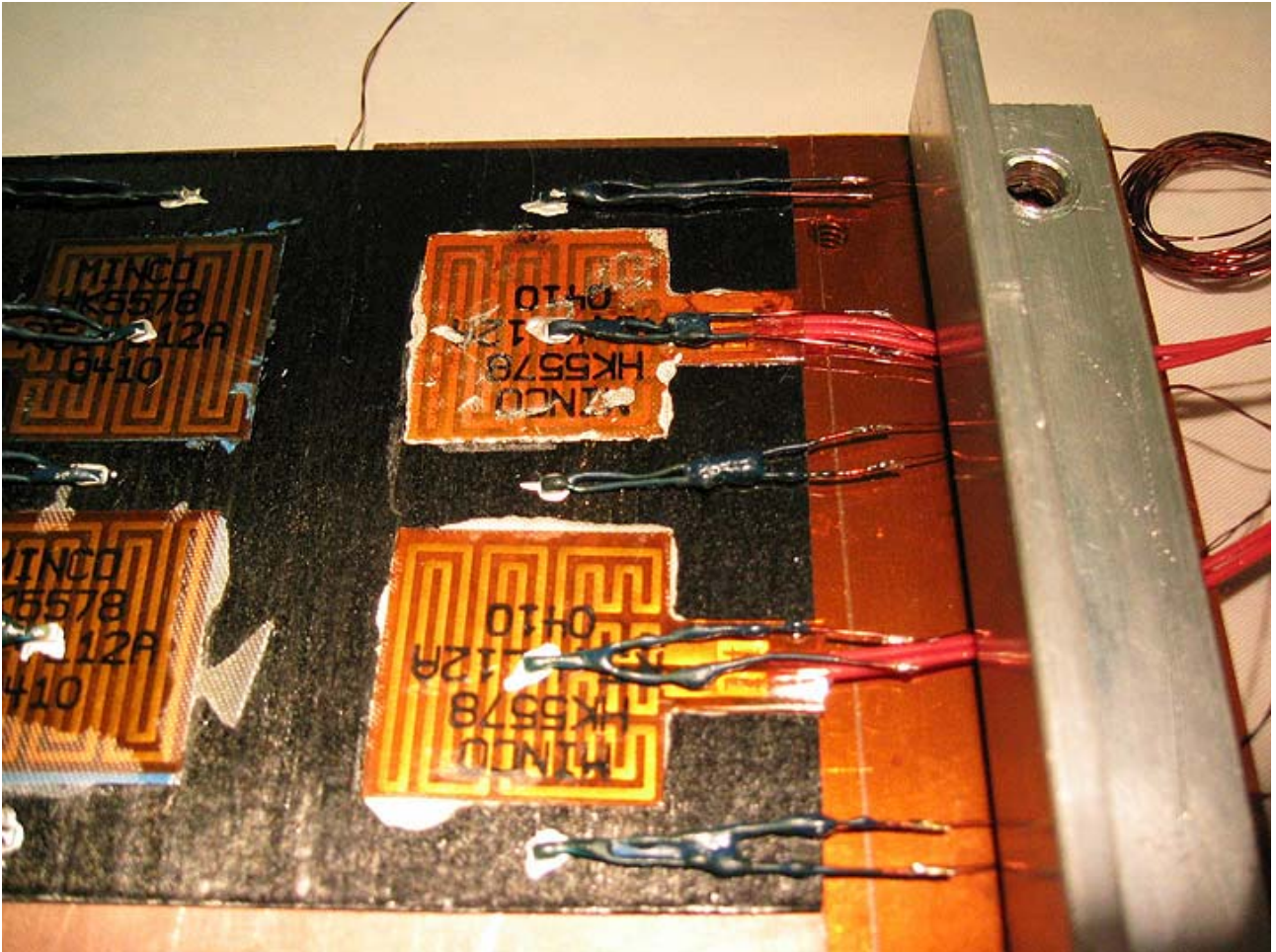


Fig. 5- Detail of the substrate with the heaters (H1-H4) over the CF. There is one RTD on the top of each heater and two RTDs attached on the substrate on its side.

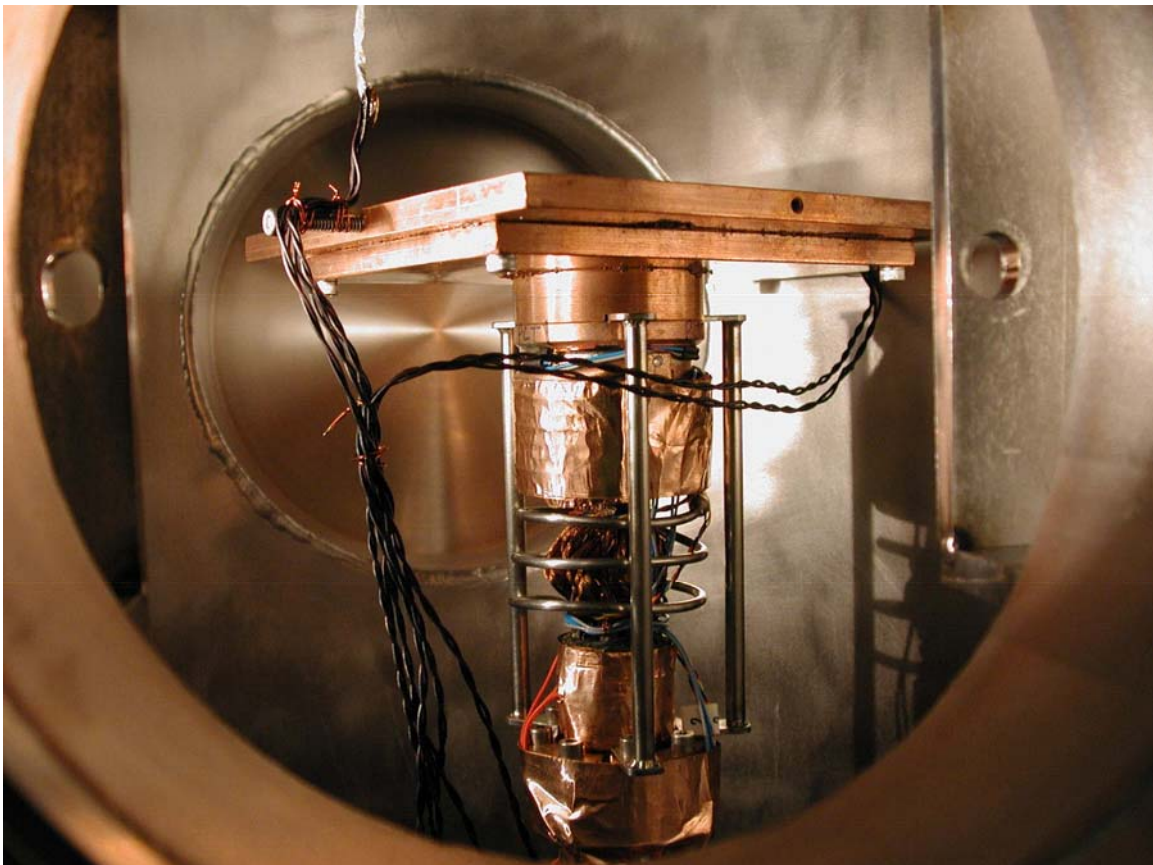


Fig. 6 - Head of the cryocooler inside the vacuum vessel

### 3. Expected thermal resistance between the heater conductor and the substrate

For heaters that are laminated between the carbon fiber and the TPG (Figure 4c), we add the thermal resistance per unit area of the kapton, epoxy, and TPG.

Table 2 – Material in Heater Test

Material	Thermal Conductivity (W/m-K)	Thickness $\mu\text{m}$	Thermal resistance per unit surface $\text{K}/(\text{W}/\text{cm}^2)$
Kapton	0.2	50	2.5
Epoxy	0.5	50	1.0
TPG	(Through-plane) 10.0	380/2	$\sim 0.2$

The calculation assumes that there is an epoxy layer with a thickness of  $50\mu\text{m}$  and a **perfect distribution of epoxy (without bubbles) between the heater and the TPG**. The TPG contribution is calculated assuming that the RTDs on the substrate are reading the temperature at the middle of the substrate between the top and the bottom surfaces (middle of cross-section). The expected thermal resistance per unit surface between the heater conductor and the substrate is (3 - 4)  $\text{K}/(\text{W}/\text{cm}^2)$

To obtain the thermal resistance of the structure in Figure 4b we have to add the specific thermal resistance of the carbon fiber layer. We assume a thickness of  $50\mu\text{m}$  and a thermal conductivity of  $0.3 \text{ W}/\text{m-K}$ . The thermal resistance is calculated to be about  $2 \text{ K}/(\text{W}/\text{cm}^2)$ . The expected specific thermal resistance between the heater element and the middle of the cross-section of the TPG is estimated to be about  $4 \text{ K}/(\text{W}/\text{cm}^2)$  for the composite structure in Figure 4c and about  $6 \text{ K}/(\text{W}/\text{cm}^2)$  for the one in Figure 4b.

### 4. Procedure to attach the heater to the substrate

The TPG substrate used for heaters 1, 2, 3, and 4 was coated on both sides with a single layer of carbon fiber. These 4 heaters were then attached to the TPG one at a time each with a different epoxy due to the different curing temperatures. The TPG sample ( $6.75 \text{ in}^2$ ) was first placed on an aluminum plate, then the heaters were epoxied to the TPG and covered with release cloth. A second aluminum plate was next placed over the sample and clamped in place with 4 spring clamps. The individual force of the clamps is approximately 25 lbs. each. The piece of TPG for heaters 5, 6, 7, and 8 was coated on one side with a single layer of carbon fiber. The heaters were attached to the bare TPG as described above and then covered with a single layer of carbon fiber.

## 5. First Test heater-substrate thermal resistance measurement

The thermal resistance between the heater and substrate is obtained from the change in temperature between the heating element and the substrate as a function of heater power. Table 3 shows the thermal resistance per unit contact area of all the heaters of the present setup.

Table 3

Heater	Thermal resistance per unit contact area	Adhesive	Heater under the Carbon Fiber Figure 4c	Heater over the Carbon Fiber Figure 4b
#	K/(W/cm <sup>2</sup> )	-	-	-
1	28	Master Bond		x
2	165	Bryte Tech BT 250E-1		x
3	220	Epo Tek H-27D		x
4	<b>10</b>	Minco 15		x
5	48	Master Bond	x	
6	<b>9</b>	Bryte Tech BT 250E-1	x	
7	<b>12</b>	Epo Tek H-27D	x	
8	<b>8</b>	Minco 15	x	

We will focus on heater number 6 because of its low thermal resistance. Next we will describe the measurement method and data analysis for heater 6. The measurement results for all the other heaters are reported in Appendix A.

### 7.1 Heater 6

Figure 7 illustrates the temperature (T6) on top of heater 6 (H6), the two RTDs T16 and T18 located near H6 and the temperatures Cu1 and Cu2 of the copper plate (Figures 4 and 6) as the power is changed.

The high thermal conductivity of the TPG substrate makes the temperature distribution uniform. The RTDs T15, T17, T19, T20 on the same substrate read almost the same values as T16 and T18. Figure 8 shows the steady state temperatures of the heating element (NiFe), the RTD T6 on top of the heater, the substrate region nearby the heater (T16 and T18) and all the other RTDs (T15, T17, T19, T20) on the substrate as a function of the heater power density. The area of the heater is  $0.75 \times 0.75 \text{ in}^2 = 3.63 \text{ cm}^2$ , but the power density is calculated using an effective area of  $0.48 \text{ in}^2 = 3.1 \text{ cm}^2$ , as published in the Minco's catalog.

The substrate temperature does not increase linearly with the heater power because of a poor thermal coupling between the copper plate and the TPG. We chose not to improve this condition because of the risk of damaging the fragile assembly. Even under these conditions, it was possible to measure the thermal resistance between the heaters and the substrates.

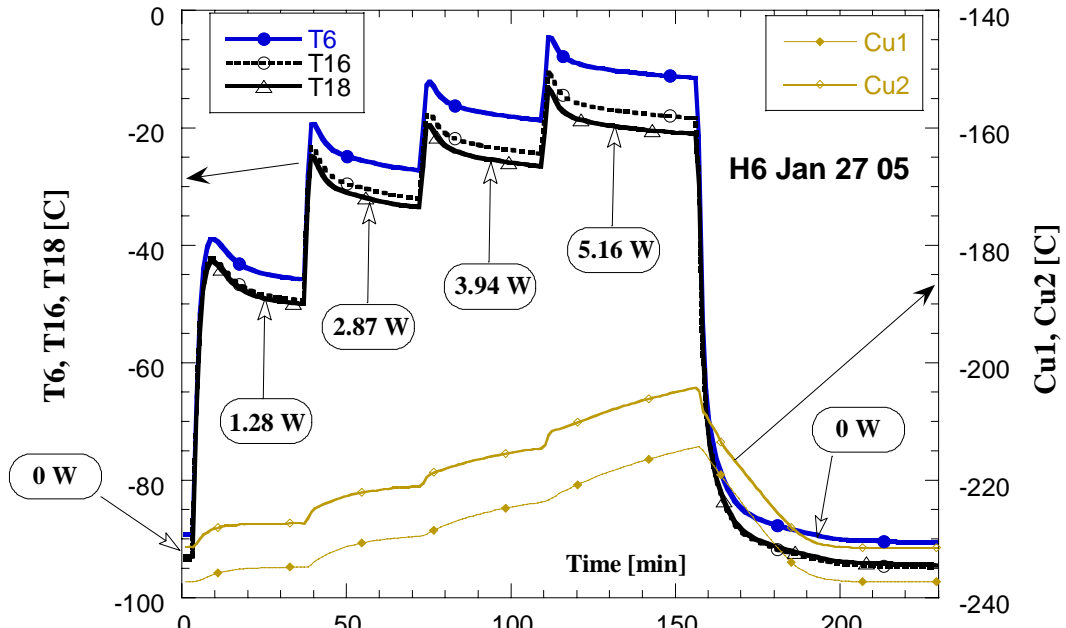


Fig. 7 - The temperature of the thermometer T6 on the top of the heater 6 and of the two thermometers on the substrate nearby the heater 6. Because of the high thermal conductivity of the TPG substrate, all the other thermometers T15, T17, T19, T20 on the same substrate read almost the same values of T16 and T18. Cu1 and Cu2 are the temperatures of the copper plate connected to the cold head of the cryocooler.

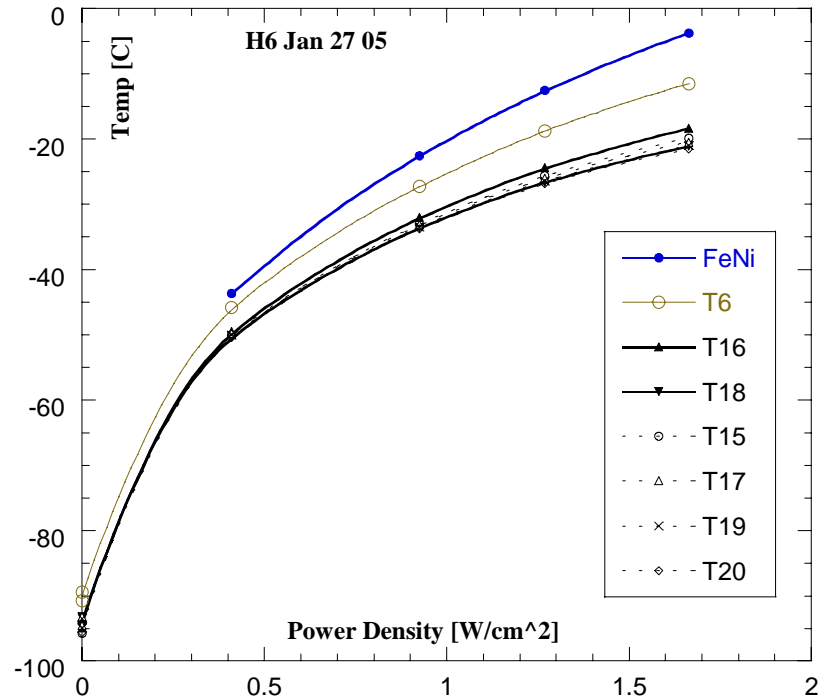


Fig. 8  
 FeNi is the heating element temperature  
 T6 is the thermometer on the top of the heater 6  
 T16 and T18 are the two thermometers on the TPG substrate nearby the heater 6  
 T15, T17, T19, T20 are the other four thermometers on the TPG substrate

Figure 9 illustrates the non-uniform distribution of the thermal grease, which caused the poor thermal contact between the copper plate and the TPG. This picture was taken after the complete measurements.

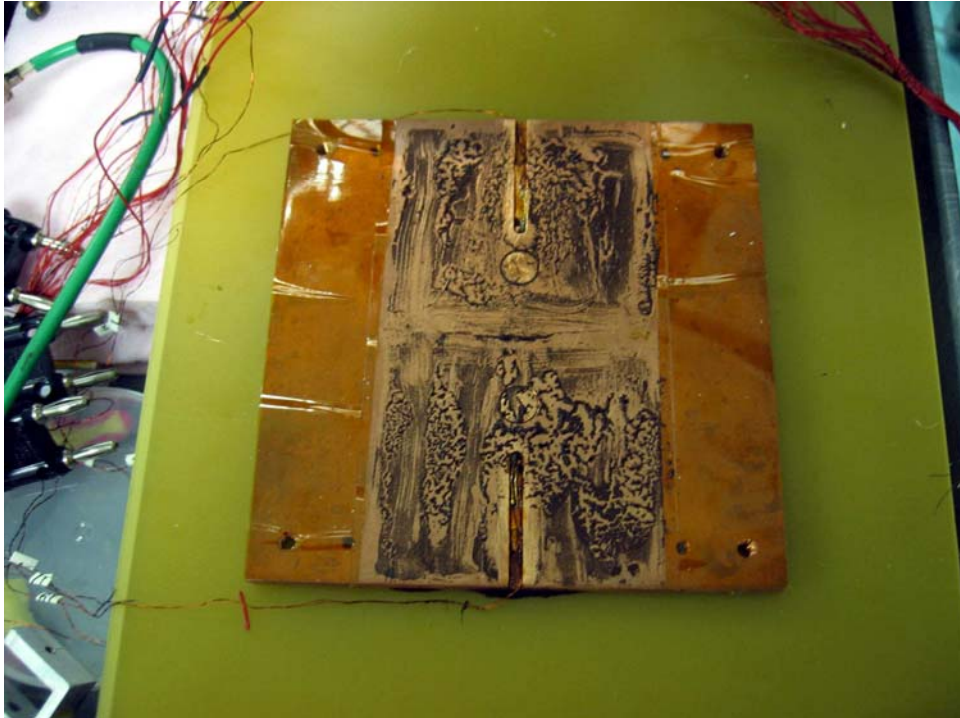


Fig.9 - Footprint of the two substrates on the copper plate. The substrates have been removed after finishing the heater-substrate thermal contact measurements for all the eight heaters.

In Figure 10 the thermal contact between heater 6 and the substrate is obtained by measuring the gradient of the temperature difference between the nickel-iron heating element and the substrate ( $\text{NiFe} - (T_{16}+T_{18})/2$ ) versus the heater power density. Also illustrated is the gradient of the temperature difference between the thermometer T6 on the top of the heater and the substrate ( $T_6 - (T_{16}+T_{18})/2$ ) versus the heater power density.

The resistance, of the heating element used for the first test apparatus, is obtained by subtracting the heater wire resistance from the total circuit resistance, measured at the power supply pins. An error of  $0.1 \, \Omega$  on the heater resistance is the source of a systematic error of about  $4 \, \text{C}$  on its temperature. This error is almost completely removed by taking the difference between two heater temperatures to calculate the temperature gradient. In Figure 10, the heater wire resistance was used as a free parameter to obtain the heating element resistance that annuls the temperature difference between the nickel-iron heating element and the thermometer T6 on the top of the heater ( $\text{NiFe} - T_6$ ) when the power density is zero. This criterion makes the reasonable hypothesis that the thermometer T6 and the heating element are at the same temperature when no heater power is supplied to the heater. This takes advantage of the lower temperature error of the RTD and allows for measuring the thermal contact that matters: i.e. the one between the heating element and the substrate. Using the data for heater 6 on Jan. 27, 05, the value of the wire resistance ( $R_w$ ) that satisfies this criterion is  $2.28 \, \Omega$ . It could be possible to have a difference of  $0.2 \, \Omega$  between two heater circuits. The gradient of the temperature difference between the nickel-iron heating element and the substrate versus the heater power density is slightly modified by this wire resistance change. For instance, continuing with the present example, this gradient is  $7.9 \, \text{K}/(\text{W}/\text{cm}^2)$  assuming a wire resistance of  $2.28 \, \Omega$  and becomes  $6.7 \, \text{K}/(\text{W}/\text{cm}^2)$  if we use the nominal wire resistance of  $2.05 \, \Omega$ . The difference between these two gradients does not contribute to knowing whether the thermal contact is good or not. We apply this method to all the first test data analysis and summarize the results in Table 4.

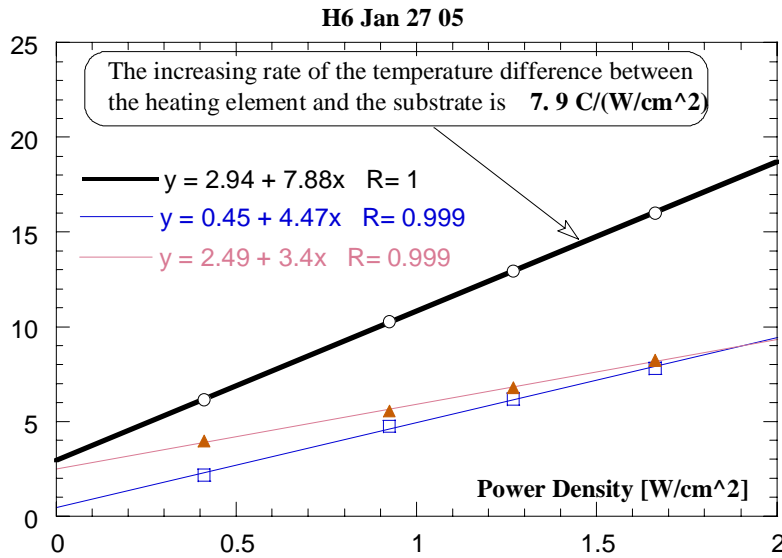


Fig. 10 The thermal contact of the heater 6 with the substrate is measured by the temperature difference between the heating element and the substrate and by the temperature difference between the top thermometer and the substrate.

- NiFe-(T16+T18)/2 is the temperature difference between the nickel-iron heating element and the substrate
- NiFe -T6 is the temperature difference between the nickel-iron heating element and the thermometer T6 on the top of the heater
- ▲— T6-(T16+T18)/2 is the temperature difference between the thermometer T6 on the top of the heater and the substrate

Table 4: Summary of all the first test measurements

Heater #	Measure	$R_w$ $\Omega$	NiFe $G_R$ $\text{K}/(\text{W}/\text{cm}^2)$	NiFe $G_o$ $\text{K}/(\text{W}/\text{cm}^2)$	Top $G_R$ $\text{K}/(\text{W}/\text{cm}^2)$	Top $G_o$ $\text{K}/(\text{W}/\text{cm}^2)$
1	Dec 20 04	1.84	22	25	13	14
	Jan 05 05	1.91	33	35	13	13
	Jan 29 05	2.87	28	20	17	15
2	Dec 27 04	2.55	149	133	87	83
	Jan 07 05	2.50	180	161	112	107
3	Jan 04 05	1.68	313	344	219	228
	Jan 04 05	2.05	129	129	79	79
4	Dec 27 04	2.10	19	18	3.3	3.1
	Dec 28 04	2.38	3.2	-1.0	3.0	2.3
	Jan 20 05	2.29	9.2	8.1	4.5	3.3
	Jan 26 05	2.27	8.0	6.6	4.1	3.5
5	Jan 06 05	2.23	48	46	45	44
	Jan 06 05	2.24	47	44	44	43
6	Jan 27 05	2.28	7.9	6.7	3.4	3.3
	Jan 28 05	2.27	9.5	8.3	3.5	3.3
7	Dec 29 04	2.27	11	9.7	6.1	5.9
	Jan 26 05	2.15	12	12	6.1	6.0
8	Jan 27 05	2.15	8.8	8.8		
	Jan 28 05	2.25	7.8	6.9		

Fig. 10 The thermal contact of the heater 6 with the substrate is measured by the gradient of the temperature difference between the heating element and the substrate. The heating element resistance is calculated subtracting the value of the wire resistance that annuls the temperature difference between the heating element and the top thermometer when the power density is zero.

The temperature difference between the thermometer on the top of the heater and the substrate is also reported.

**$R_w$**  = **Wire Resistance** used as a free parameter to obtain the heating element resistance that annuls the temperature difference between the nickel-iron heating element and the thermometer on the top of the heater, when the power density is zero.

**NiFe  $G_R$**  = **Gradient** of the temperature difference between the nickel-iron heating element and the substrate versus the heater power density. The heating element resistance is obtained by subtracting the wire resistance from the heater circuit resistance  $R_w$ .

**NiFe  $G_o$**  = **Gradient** of the temperature difference between the nickel-iron heating element and the substrate versus the heater power density. The heating element resistance is obtained by subtracting the nominal wire resistance  $2.05 \Omega$  from the wire resistance of the heater circuit.

**Top  $G_R$**  = **Gradient** of the temperature difference between the thermometer on the top of the heater and the substrate versus the heater power density. The heating element resistance used to calculate the power density is obtained subtracting the wire resistance  $R_w$  from the resistance of the heater circuit.

**Top  $G_o$**  = **Gradient** of the temperature difference between the thermometer on the top of the heater and the substrate versus the heater power density. The heating element resistance used to calculate the power density is obtained subtracting the nominal wire resistance  $2.05 \Omega$  from the resistance of the heater circuit.

The thermometer on top of heater 8 did not work. The resistance  $R_w$  has been selected to have the temperature of the heating element about 1 C above the substrate when the power density is zero.

## 6. Second Test Apparatus

Figure 11 defines the heater and RTD labels and the glue used to attach each heater to the TPG substrate used for the second heater test. The TPG substrate is encapsulated with carbon fiber (CF) and installed, as the first test, on the copper plate. Figure 12 shows a picture of the substrate used for the second test, before and after covering the heaters and thermometers with the CF layer. As Figure 12b shows, three RTD accidentally got disconnected from the substrate. Subsequently, T7 and T8 have been successfully reconnected and work normally. However, T10 reads systematically 3 - 4 C higher than the other thermometers when no power is supplied to the heaters and T9 does not work. Due to the high thermal conductivity of TPG, the four RTDs (T5, T6, T7, T8) are sufficient to measure the substrate temperature.

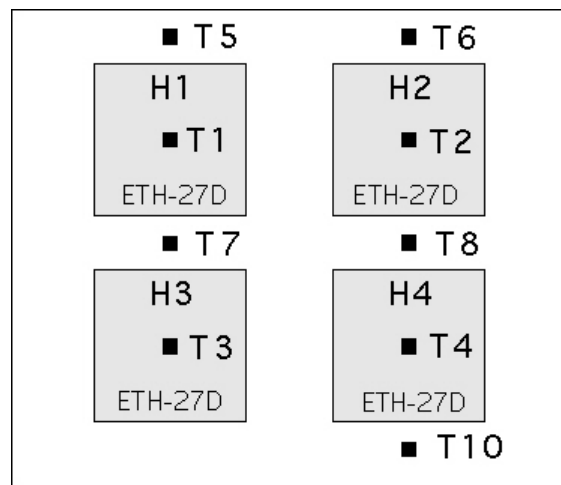
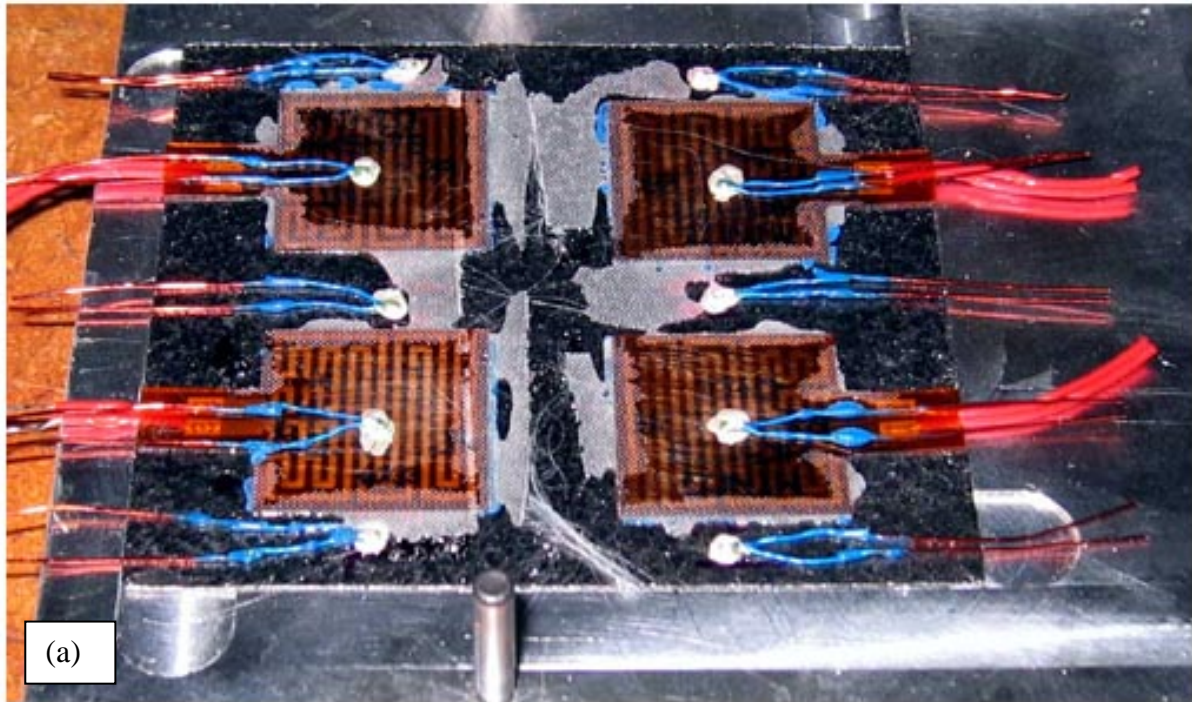
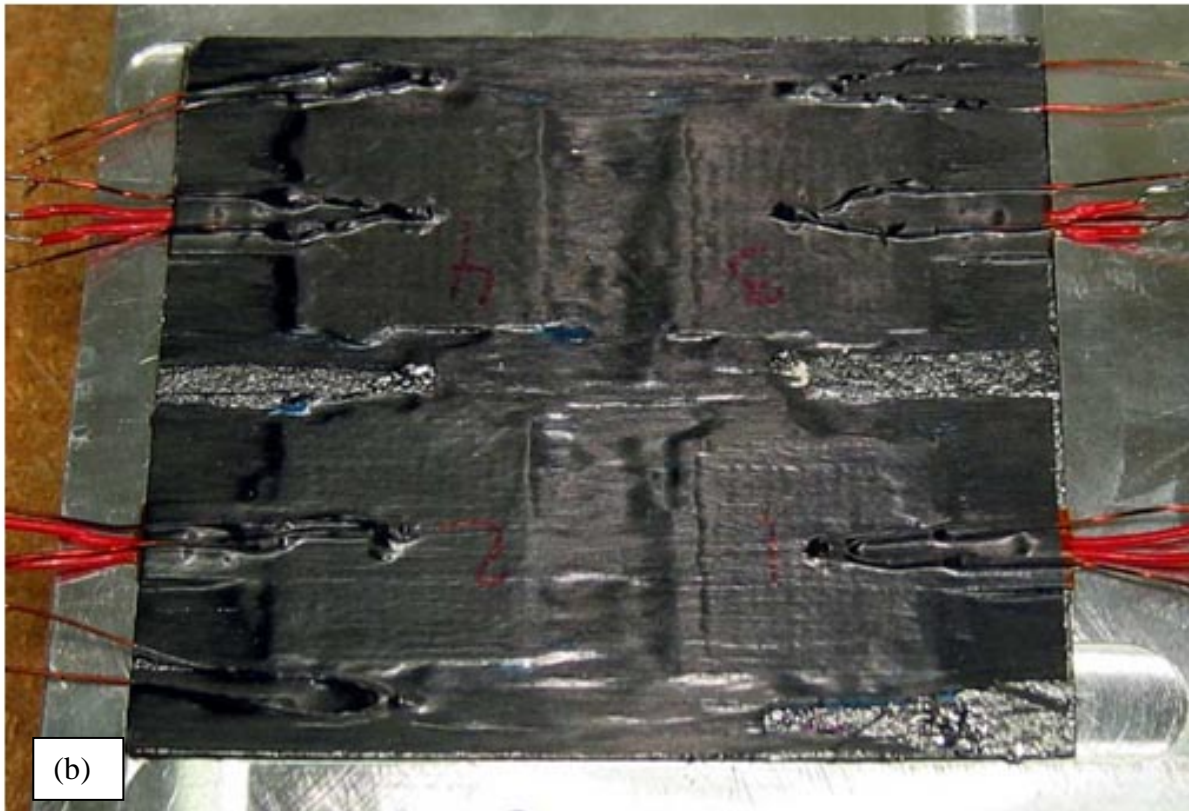


Fig.11 - Layout of the TPG sample used for the second test. The H1-H4 heaters are glued on the TPG below the CF. The glue type is marked on each heater. RTD T9 was damaged and not replaced due to the high thermal conductivity of the TPG.



(a)



(b)

Fig.12

a) The TPG substrate before covering the four heaters and the ten RTD with the carbon fiber layer.

b) Carbon fiber layer covering the RTD and the heaters. Three RTD got accidentally disconnected from the substrate. T7 and T8 have been successfully reconnected, T9 does not work and T10 reads systematically a temperature a few degree higher than all the other thermometers. T5, T6, T7, T8 read almost the same temperature due to the high thermal conductivity of the TPG and are sufficient to measure the substrate temperature.

## 7. Second Test heater-substrate thermal resistance measurement

As for the first test, the thermal resistance between the heater and substrate is obtained from the change in temperature between the heating element and the substrate as a function of heater power. The heating element temperature is calculated by equation (1), measuring its electrical resistance. The electrical resistances  $R_o$  were measured bringing each heater at 0° C, controlling the cryocooler head temperature, a cross check of these values has been done also from the electrical resistance of each heater at 24° C and equation (1). The electrical resistances  $R_o$  and the thermal resistance per unit contact area of all the heaters of the second test setup are reported in the Table 5.

Table 5

Heater	Resistance $R_o$ @ 0 C	Thermal resistance per unit contact area	Adhesive
#	$\Omega$	K/(W/cm <sup>2</sup> )	-
1	5.266	<b>7.6</b>	Epo Tek H-27D
2	5.260	<b>7.4</b>	Epo Tek H-27D
3	5.208	<b>8.5</b>	Epo Tek H-27D
4	5.345	<b>8.2</b>	Epo Tek H-27D

As in section 5.1, we will describe the measurements on heater number 1 and report in Appendix B the results for all the other heaters of the second test.

### 7.1 Heater 1

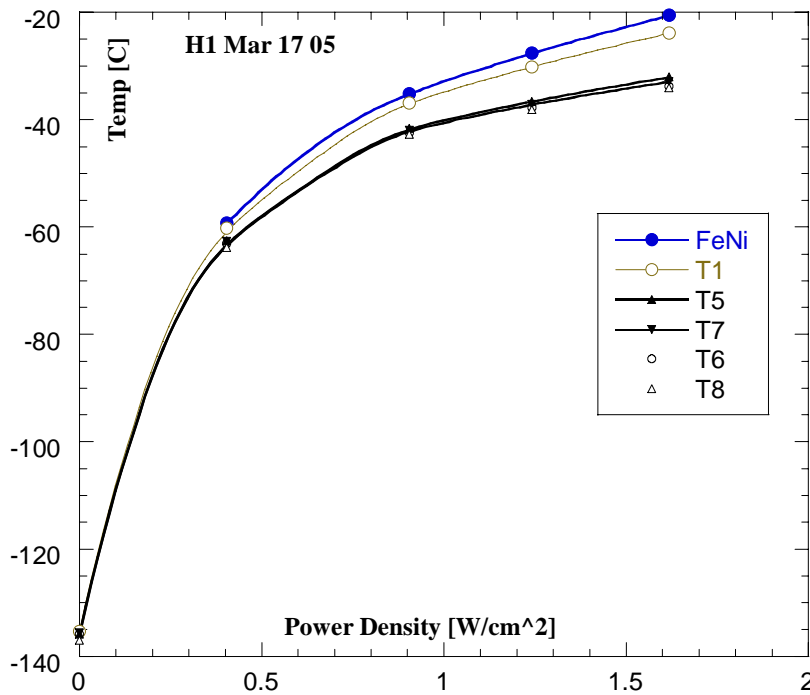


Fig. 13

FeNi is the heating element temperature

T1 is the thermometer on the top of the heater 1

T5 and T7 are the two thermometers on the TPG substrate nearby the heater 1

heating element resistances by the four-wire method.

Figure 13 shows the steady state temperatures of the heating element (NiFe), the RTD T1 on top of the heater, the substrate region nearby the heater (T5 and T7) and the other two RTDs (T6, T8) on the substrate as a function of the heater power density. The thermal contact of heater 1 with the substrate is measured by the gradient of the temperature difference between the heating element and the substrate (Figure 14). Please note that the present data prove the equality between the heating element temperature and one of the thermometers T1 on top of the heater when the power density is zero. We made this hypothesis to analyze the first test data, because there were not enough pins to measure the

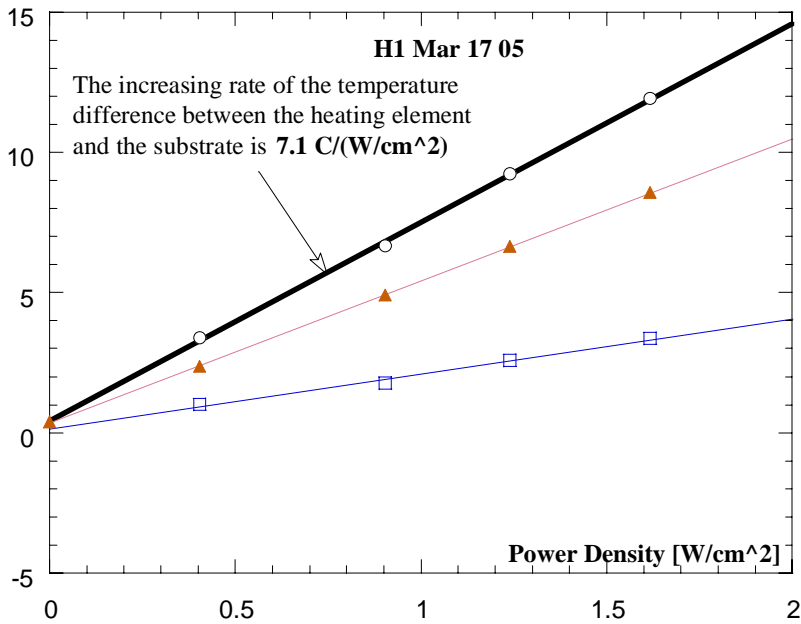
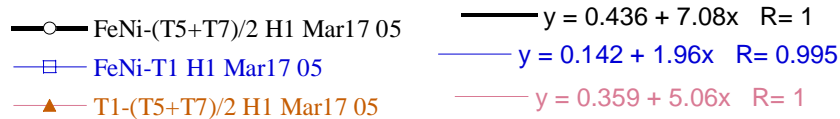


Fig. 14



## 6. Conclusion

Three of four heaters (H6, H7, H8) that were attached directly on the TPG substrate had a good thermal contact. The second group of four heaters was attached on the carbon fiber covering the substrate and only one heater from this group had an acceptable thermal bond to the TPG. The configuration illustrated in Figure 4c is the preferred design. A second test with a new set of four heaters, mounted directly on a TPG substrate (Figure 4c), proves the bonding procedure reproducibility, because all four heaters gave good thermal contact. All these thermal contact measurements have been done with the sample under vacuum, because the TPG substrate is supposed to work under vacuum. So the majority of the gas trapped, at atmospheric pressure, between the heater and the TPG has been removed. It is reasonable to think that some of the epoxy bubbles, left between the heater and the TPG by the gluing process, broke.

## References

1. Howell, J., et al, "Status of the Substrate Temperature control System," BTeV Document 2880, April 2004.
2. Marinelli, M., "Thermal Resistance of the Contact Between the Minco Heater and the TPG," BTeV Document 3022, July 2003.
3. Marinelli, M., Ruschman, M., Wong, M., "Heater / Epoxy Test", BTeV Document 3023, April 2004

## Appendix A: Fist Test Measurements

### A1 - Heater 1

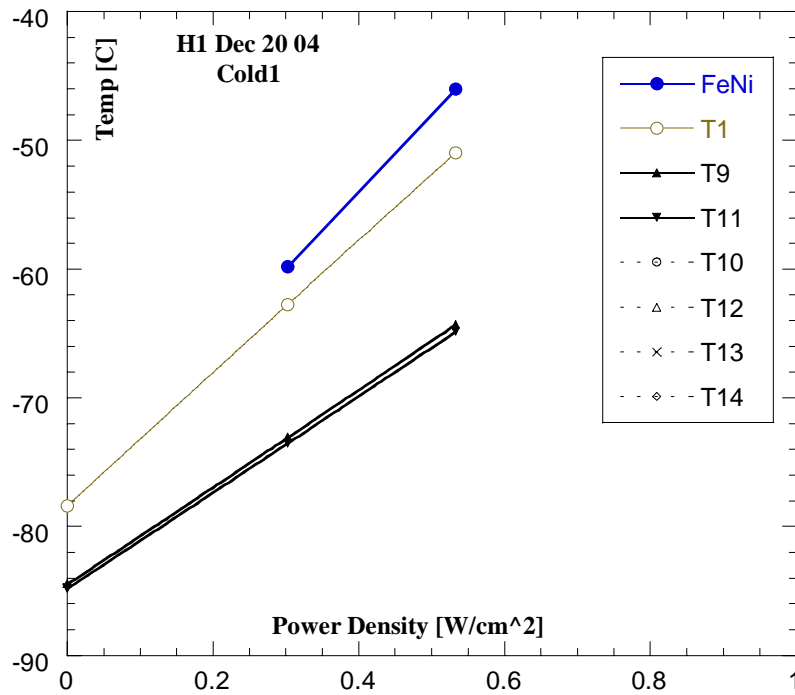


Fig. A1

FeNi is the heating element temperature

T1 is the thermometer on the top of the heater 1

T9 and T11 are the two thermometers on the TPG substrate nearby the heater 1

T10, T12, T13, T14 are the other four thermometers on the TPG substrate

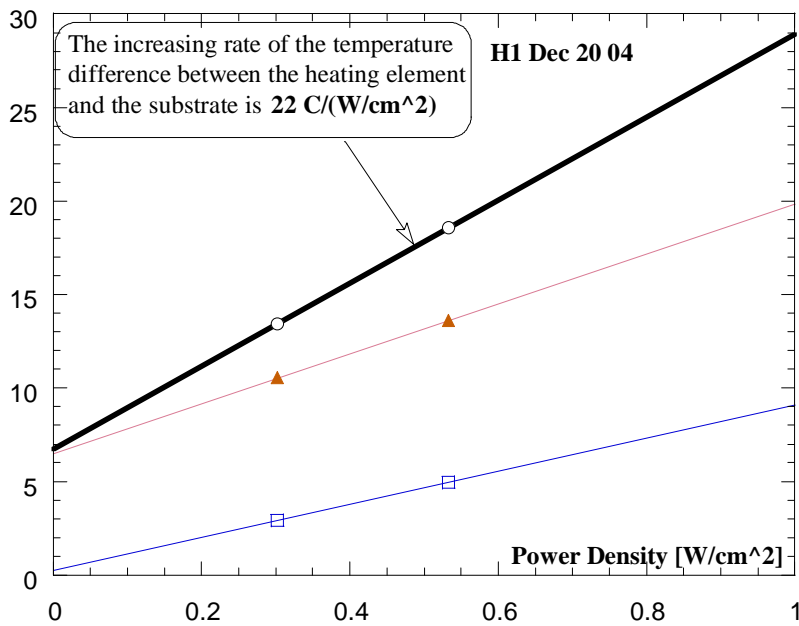


Fig. A2

—○— FeNi-(T9+T11)/2 H1 Dec20	— y = 6.74 + 22.2x R= 1
—□— FeNi-T1 H1 Dec20	— y = 0.247 + 8.84x R= 1
—▲— T1-(T9+T11)/2 H1 Dec20	— y = 6.5 + 13.3x R= 1

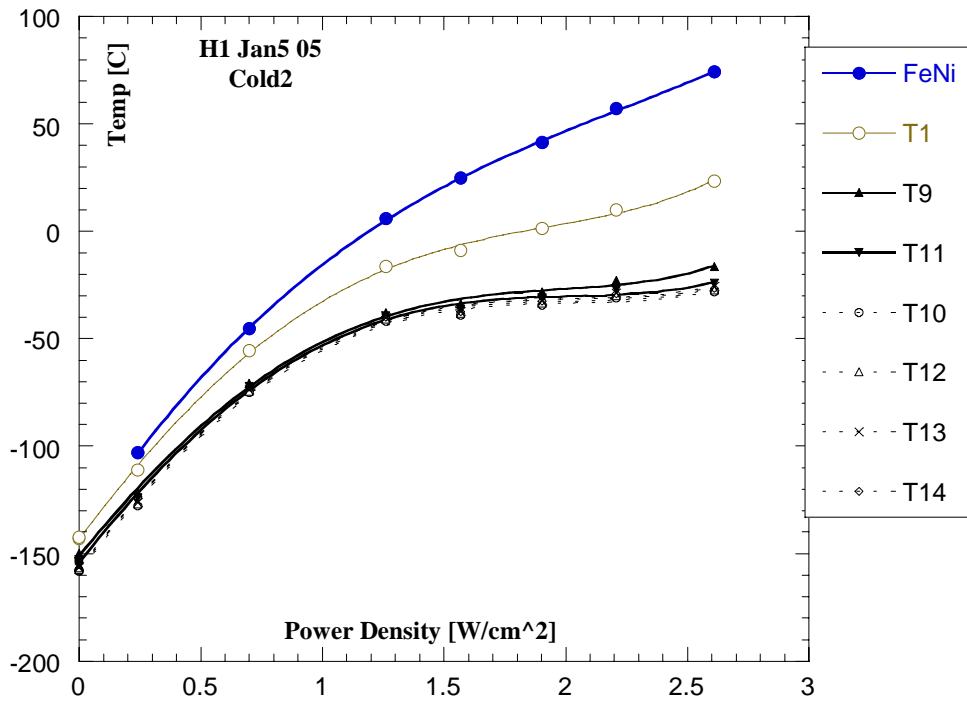


Fig. A3

FeNi is the heating element temperature

T1 is the thermometer on the top of the heater 1

T9 and T11 are the two thermometers on the TPG substrate nearby the heater 1

T10, T12, T13, T14 are the other four thermometers on the TPG substrate

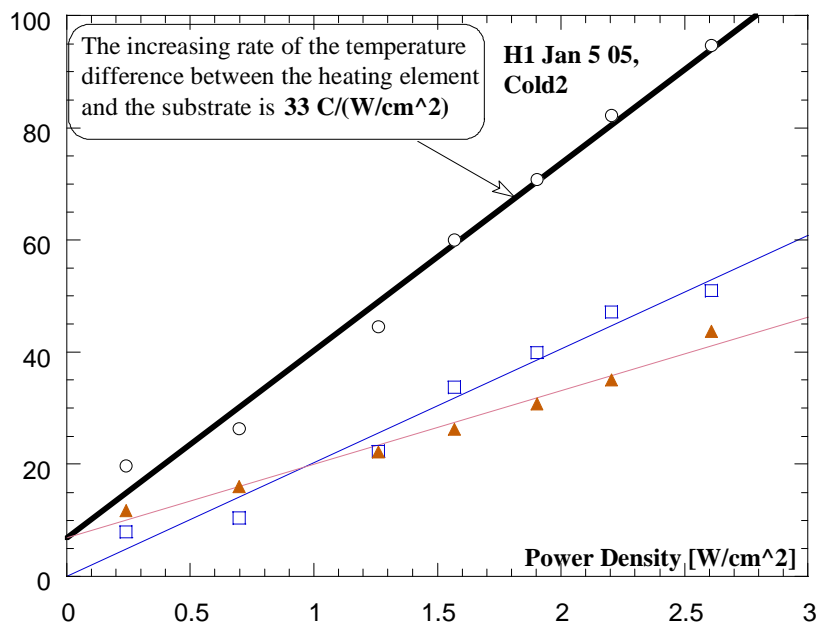


Fig. A4

—○— FeNi-(T9+T11)/2 H1 Cold2	— $y = 6.84 + 33.4x$ $R = 0.993$
—□— FeNi-T1 H1 Cold2	— $y = -0.064 + 20.3x$ $R = 0.986$
—▲— T1-(T9+T11)/2 H1 Cold2	— $y = 6.91 + 13.1x$ $R = 0.99$

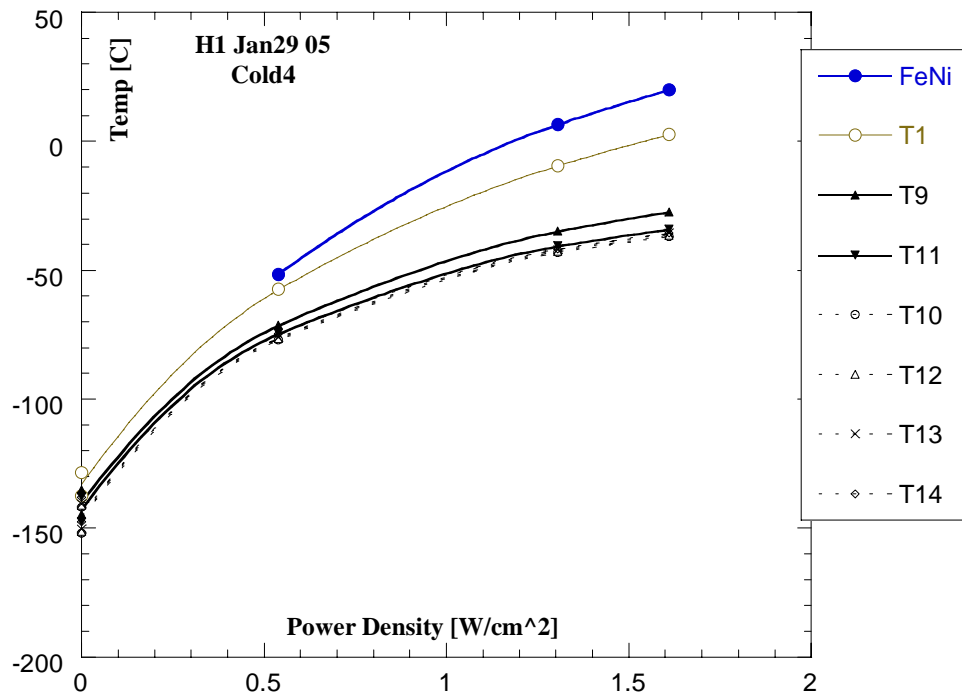


Fig. A5

FeNi is the heating element temperature

T1 is the thermometer on the top of the heater 1

T9 and T11 are the two thermometers on the TPG substrate nearby the heater 1

T10, T12, T13, T14 are the other four thermometers on the TPG substrate

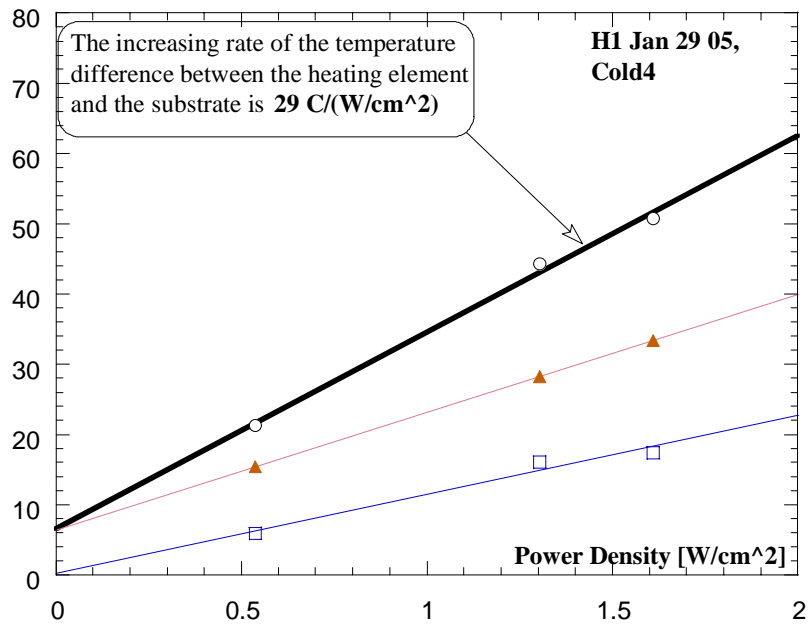


Fig. A6

—○— FeNi-(T9+T11)/2 H1 Cold4	— $y = 6.52 + 28x$ $R = 0.997$
—□— FeNi-T1 H1 Cold4	— $y = 0.148 + 11.3x$ $R = 0.985$
—▲— T1-(T9+T11)/2 H1 Cold4	— $y = 6.37 + 16.8x$ $R = 1$

## A2 - Heater 2

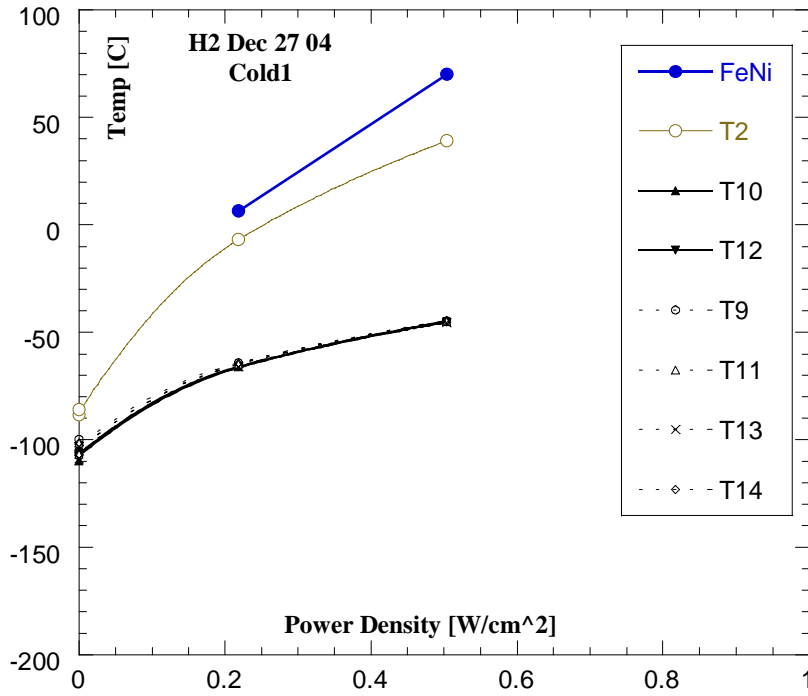


Fig. A7

FeNi is the heating element temperature

T2 is the thermometer on the top of the heater 2

T10 and T12 are the two thermometers on the TPG substrate nearby the heater 2

T9, T11, T13, T14 are the other four thermometers on the TPG substrate

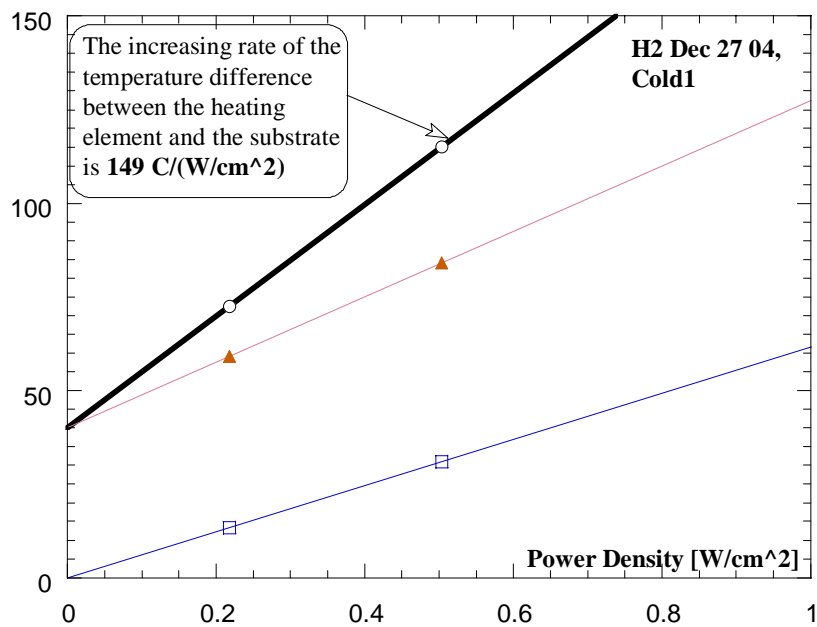


Fig. A8

—○— FeNi-(T10+T12)/2 H2 Cold1	— y = 40 + 149x R= 1
—□— FeNi-T2 H2 Cold1	— y = -0.137 + 61.8x R= 1
—▲— T2-(T10+T12)/2 H2 Cold1	— y = 40.1 + 87.3x R= 1

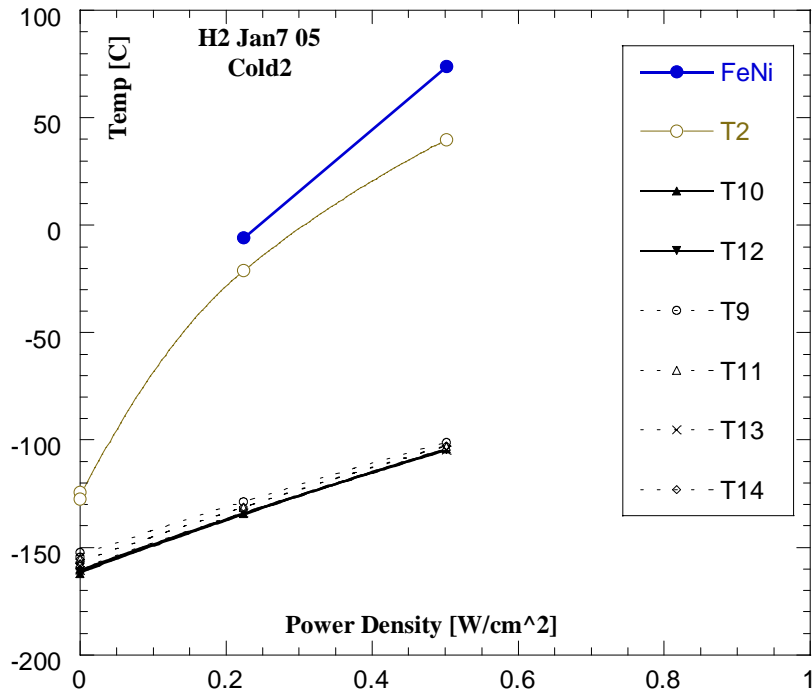


Fig. A9

FeNi is the heating element temperature

T2 is the thermometer on the top of the heater 2

T10 and T12 are the two thermometers on the TPG substrate nearby the heater 2

T9, T11, T13, T14 are the other four thermometers on the TPG substrate

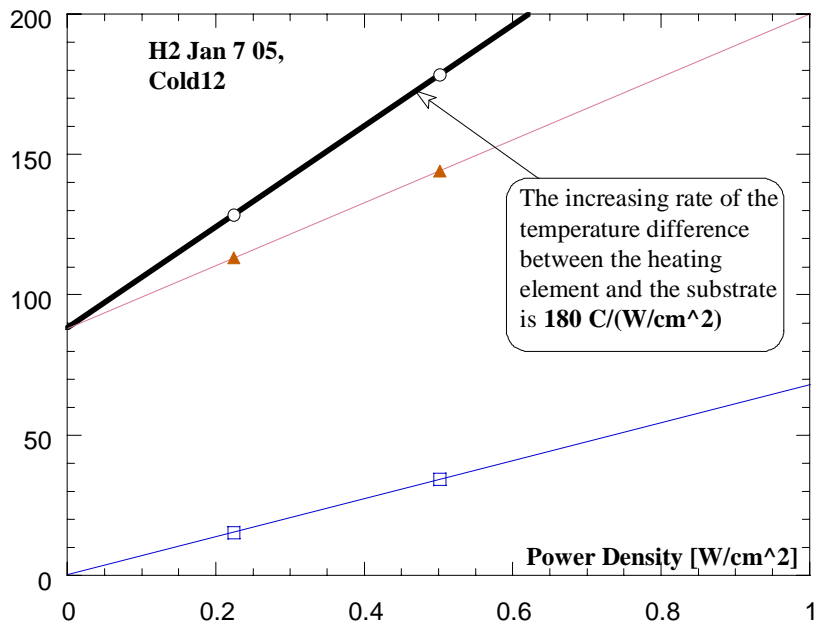


Fig. A10

—○— FeNi-(T10+T12)/2 H2 Cold2	— y = 88.2 + 180x R= 1
—□— FeNi-T2 H2 Cold1	— y = 0.156 + 67.8x R= 1
—▲— T2-(T10+T12)/2 H2 Cold2	— y = 88.1 + 112x R= 1

### A3 - Heater 3

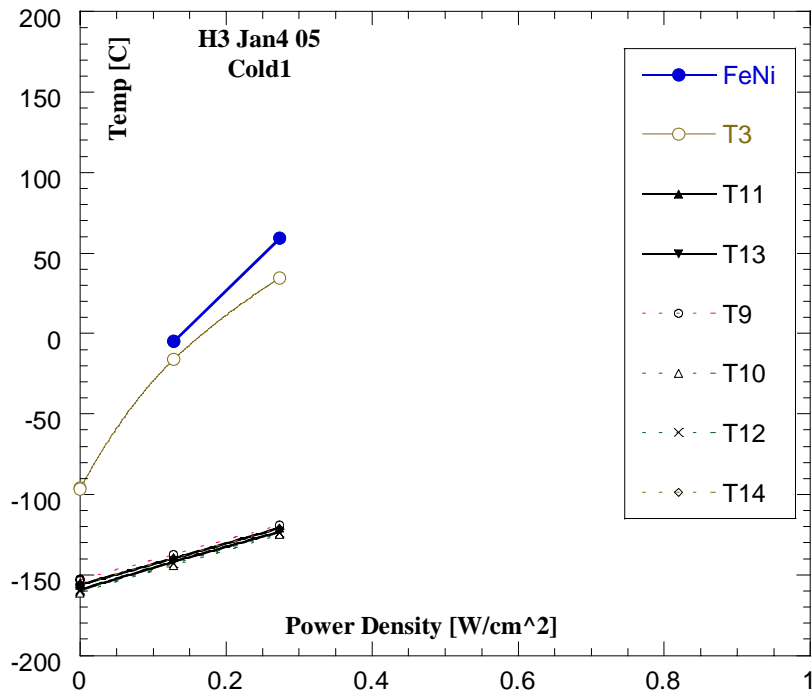


Fig. A11

FeNi is the heating element temperature

T3 is the thermometer on the top of the heater 3

T11 and T13 are the two thermometers on the TPG substrate nearby the heater 3

T9, T10, T12, T14 are the other four thermometers on the TPG substrate

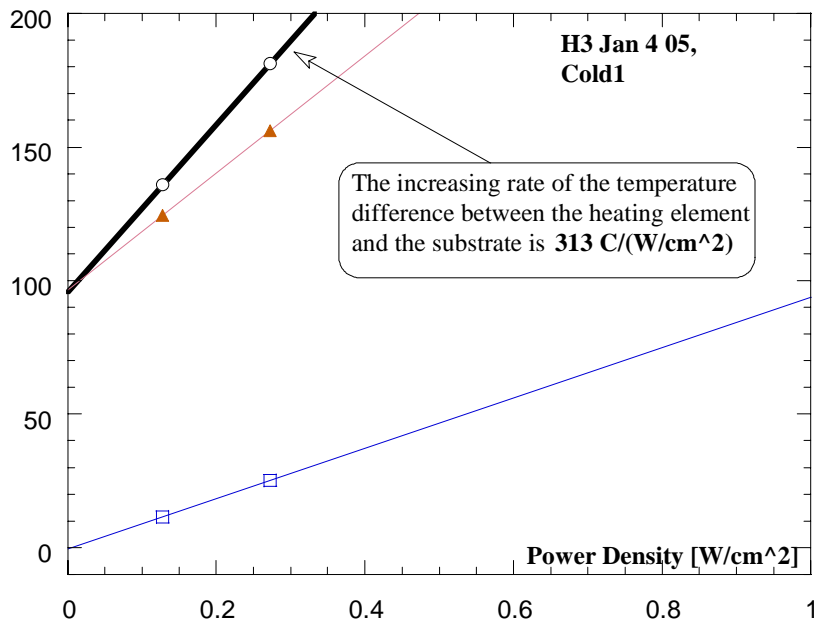


Fig. A12

—○— FeNi-(T11+T13)/2 H3 Cold2	— y = 95.8 + 313x R= 1
—□— FeNi-T3 H3 Cold2	— y = -0.677 + 94.5x R= 1
—▲— T3-(T11+T13)/2 H3 Cold2	— y = 96.5 + 219x R= 1

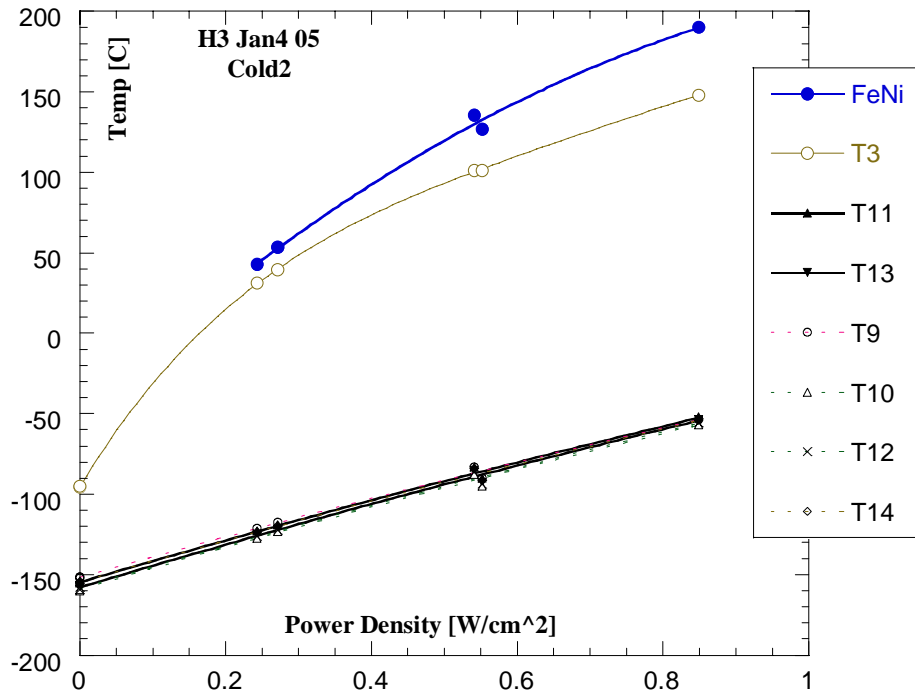


Fig. A13

FeNi is the heating element temperature

T3 is the thermometer on the top of the heater 3

T11 and T13 are the two thermometers on the TPG substrate nearby the heater 3

T9, T10, T12, T14 are the other four thermometers on the TPG substrate

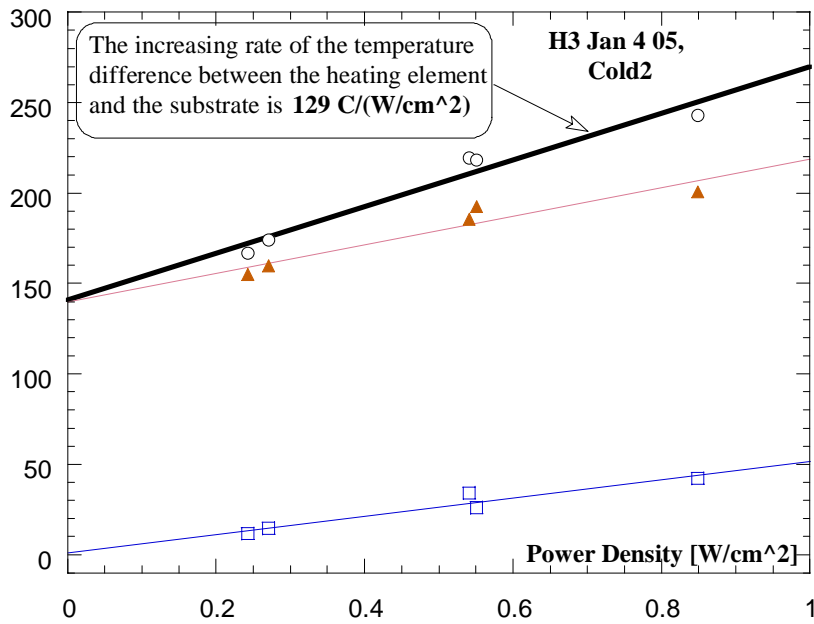


Fig. A14

—○— FeNi-(T11+T13)/2 H3 Cold2	— y = 141 + 129x R= 0.975
—□— FeNi-T3 H3 Cold2	— y = 0.969 + 50.3x R= 0.962
—▲— T3-(T11+T13)/2 H3 Cold2	— y = 140 + 78.5x R= 0.955

## A4 - Heater 4

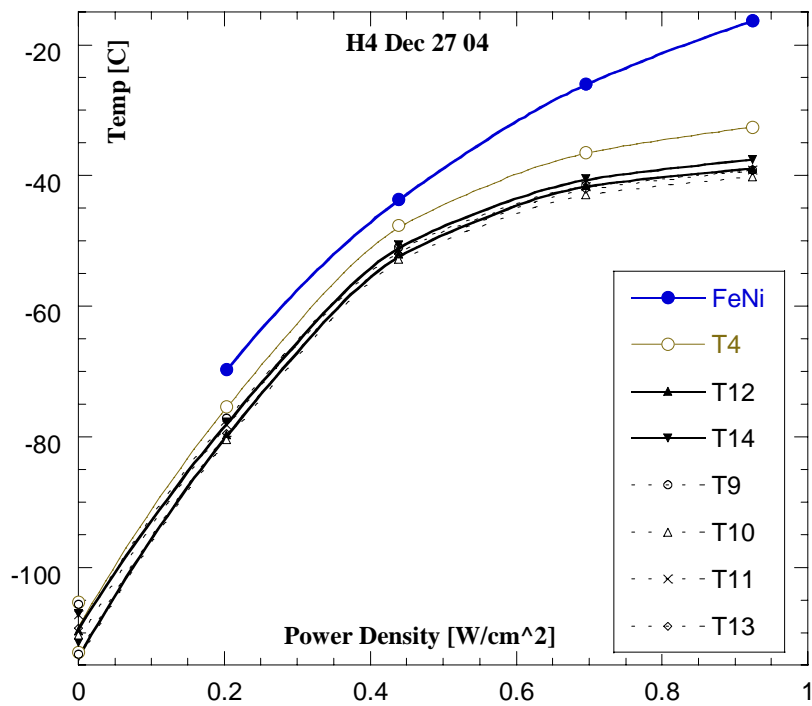


Fig. A15

FeNi is the heating element temperature

T4 is the thermometer on the top of the heater 4

T12 and T14 are the two thermometers on the TPG substrate nearby the heater 4

T9, T10, T11, T13 are the other four thermometers on the TPG substrate

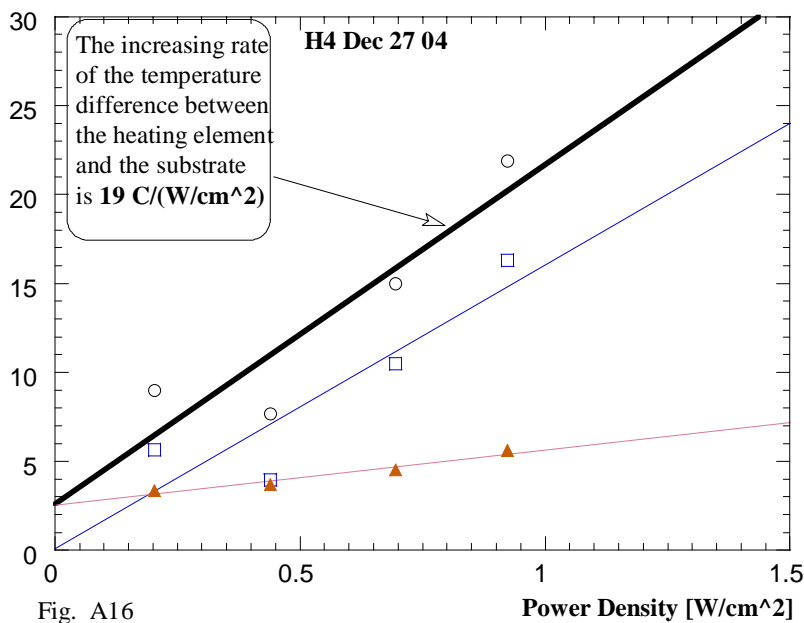


Fig. A16

—○— FeNi-(T12+T14)/2 H4 Cold5	— y = 2.61 + 19.1x R= 0.914
—□— FeNi-T4 H4 Cold5	— y = 0.0903 + 15.9x R= 0.898
—▲— T4-(T12+T14)/2 H4 Cold5	— y = 2.52 + 3.12x R= 0.975

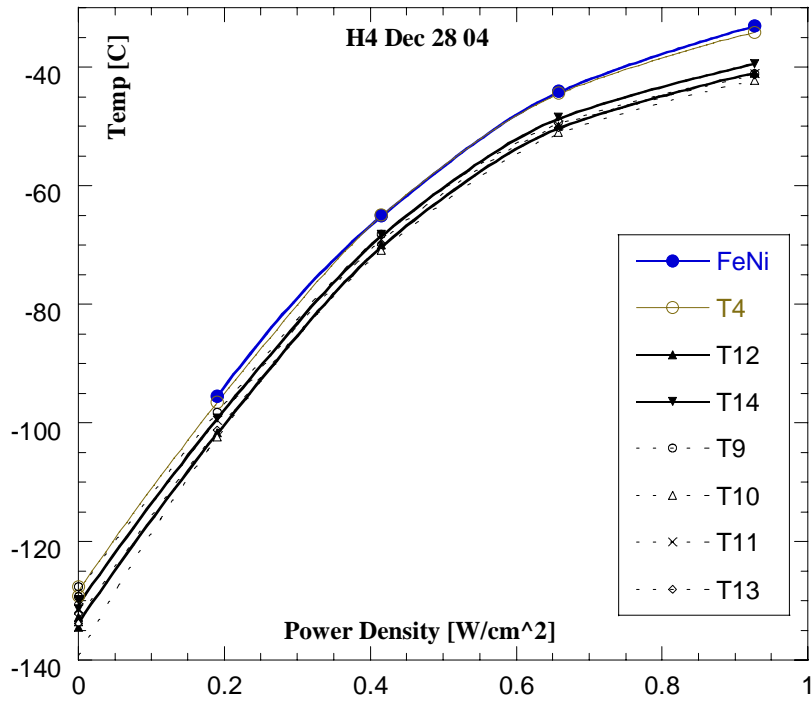


Fig. A17

FeNi is the heating element temperature

T4 is the thermometer on the top of the heater 4

T12 and T14 are the two thermometers on the TPG substrate nearby the heater 4

T9, T10, T11, T13 are the other four thermometers on the TPG substrate

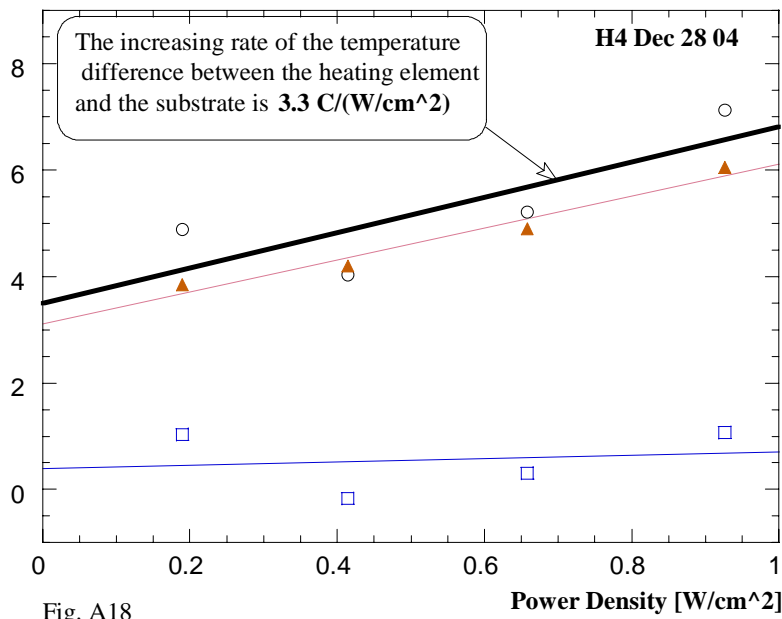


Fig. A18

—○— FeNi-(T12+T14)/2 H4 Cold5	— $y = 3.5 + 3.32x$ $R = 0.806$
—□— FeNi-T4 H4 Cold5	— $y = 0.389 + 0.318x$ $R = 0.169$
—▲— T4-(T12+T14)/2 H4 Cold5	— $y = 3.11 + 3x$ $R = 0.98$

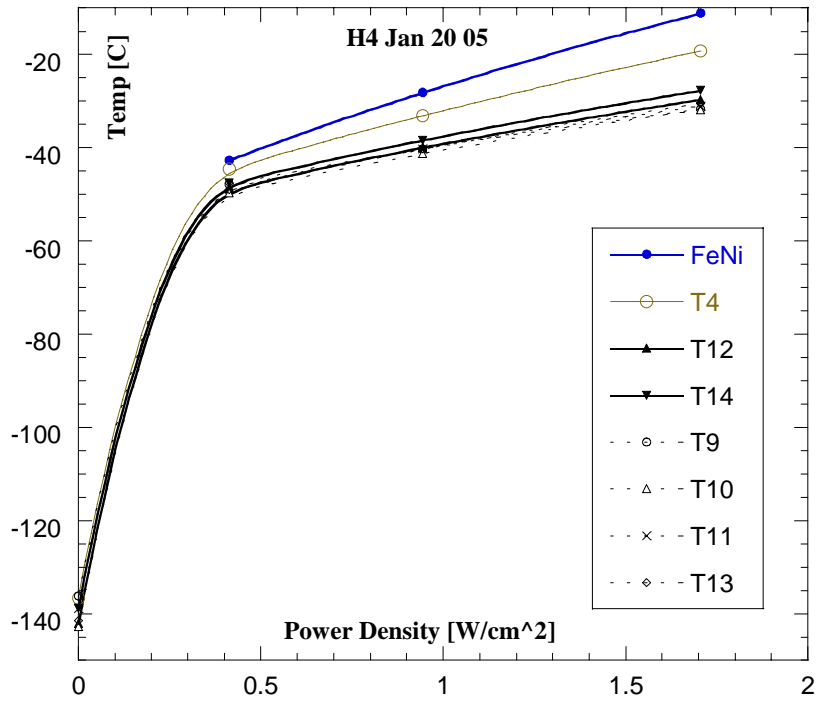


Fig. A19

FeNi is the heating element temperature

T4 is the thermometer on the top of the heater 4

T12 and T14 are the two thermometers on the TPG substrate nearby the heater 4

T9, T10, T11, T13 are the other four thermometers on the TPG substrate

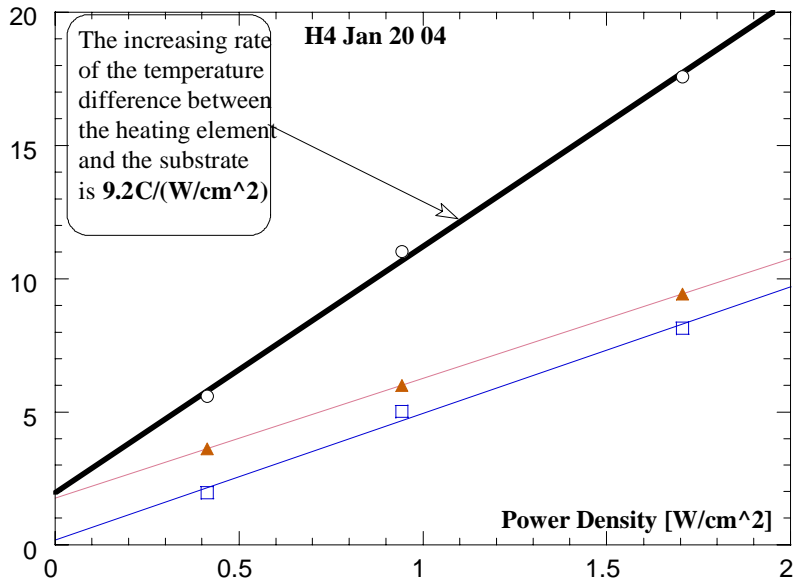


Fig. A20

—○— FeNi-(T12+T14)/2 H4 Cold5

—□— FeNi-T4 H4 Cold5

—▲— T4-(T12+T14)/2 H4 Cold5

—  $y = 1.96 + 9.23x$   $R = 0.999$

—  $y = 0.195 + 4.75x$   $R = 0.995$

—  $y = 1.77 + 4.48x$   $R = 1$

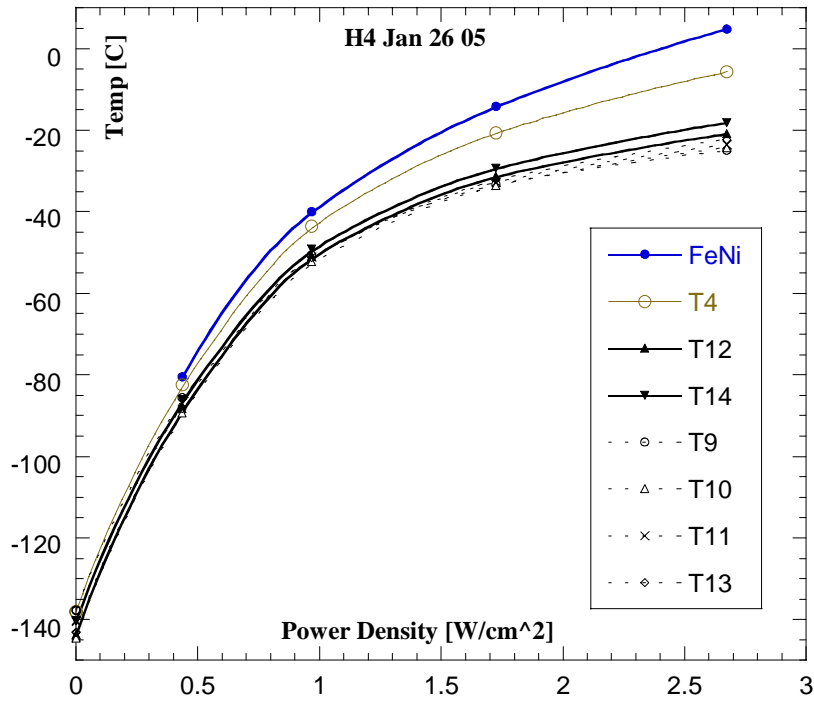


Fig. A21

FeNi is the heating element temperature

T4 is the thermometer on the top of the heater 4

T12 and T14 are the two thermometers on the TPG substrate nearby the heater 4

T9, T10, T11, T13 are the other four thermometers on the TPG substrate

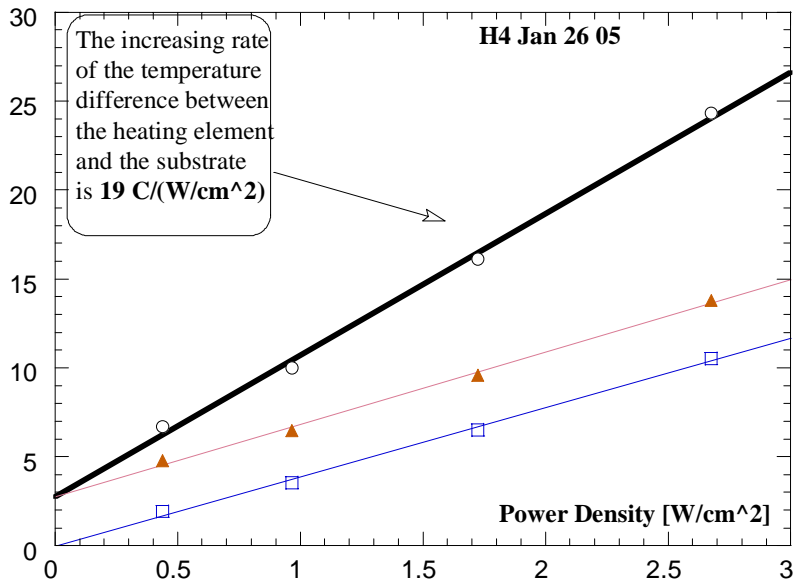


Fig. A22

—○— FeNi-(T12+T14)/2 H4 Cold5	— $y = 2.75 + 7.95x$ $R = 0.998$
—□— FeNi-T4 H4 Cold5	— $y = -0.0131 + 3.89x$ $R = 0.998$
—▲— T4-(T12+T14)/2 H4 Cold5	— $y = 2.76 + 4.06x$ $R = 0.998$

## A5 - Heater 5

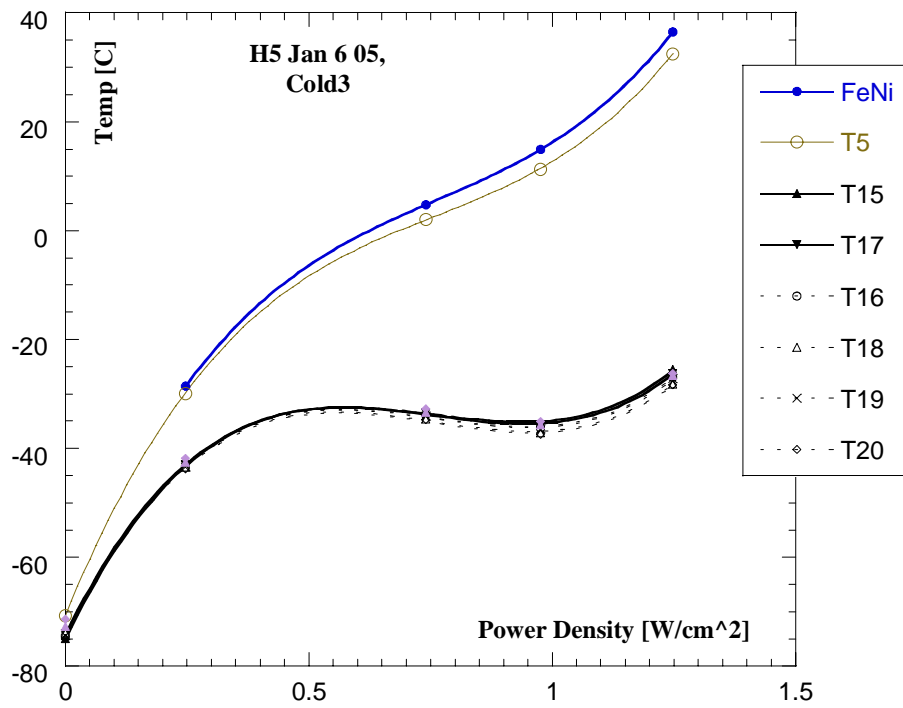


Fig. A23

FeNi is the heating element temperature

T5 is the thermometer on the top of the heater 5

T15 and T17 are the two thermometers on the TPG substrate nearby the heater 5

T16, T18, T19, T20 are the other four thermometers on the TPG substrate

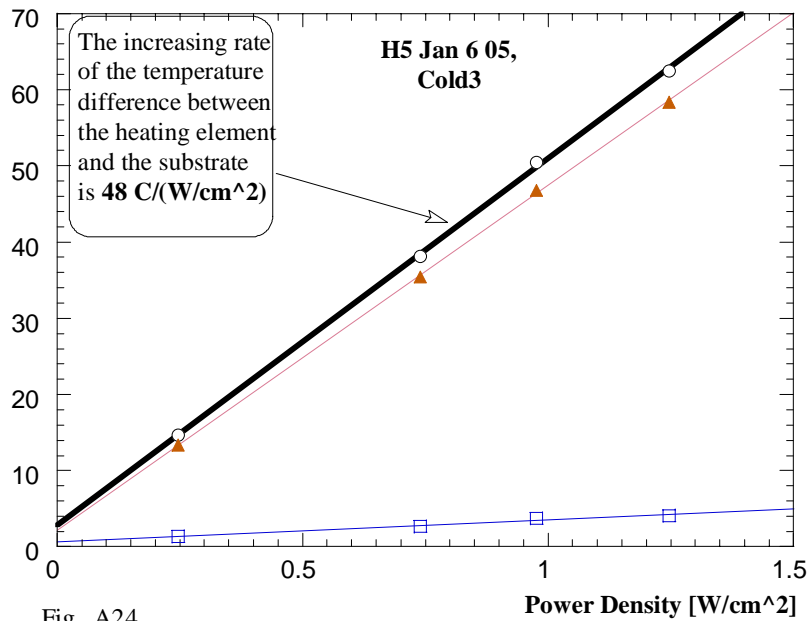


Fig. A24

—○— FeNi-(T15+T17)/2 H5 Jan6

—□— FeNi-T5 H5 Jan6

—▲— T5-(T15+T17)/2 H5 Jan6

— y = 2.88 + 48.1x R= 1

— y = 0.68 + 2.82x R= 0.988

— y = 2.2 + 45.2x R= 1

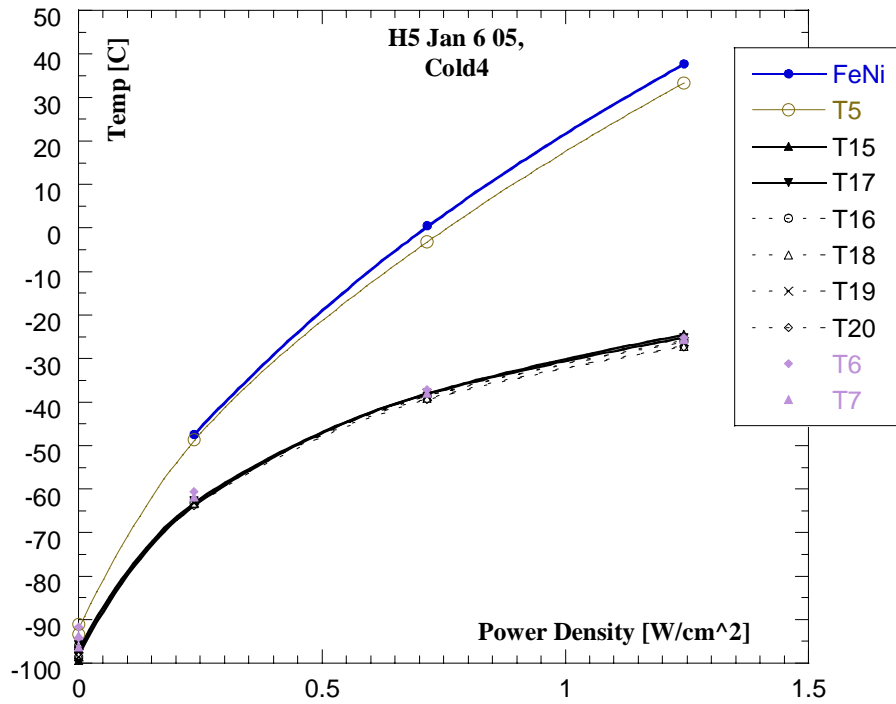


Fig. A25

FeNi is the heating element temperature

T5 is the thermometer on the top of the heater 5

T15 and T17 are the two thermometers on the TPG substrate nearby the heater 5

T16, T18, T19, T20 are the other four thermometers on the TPG substrate

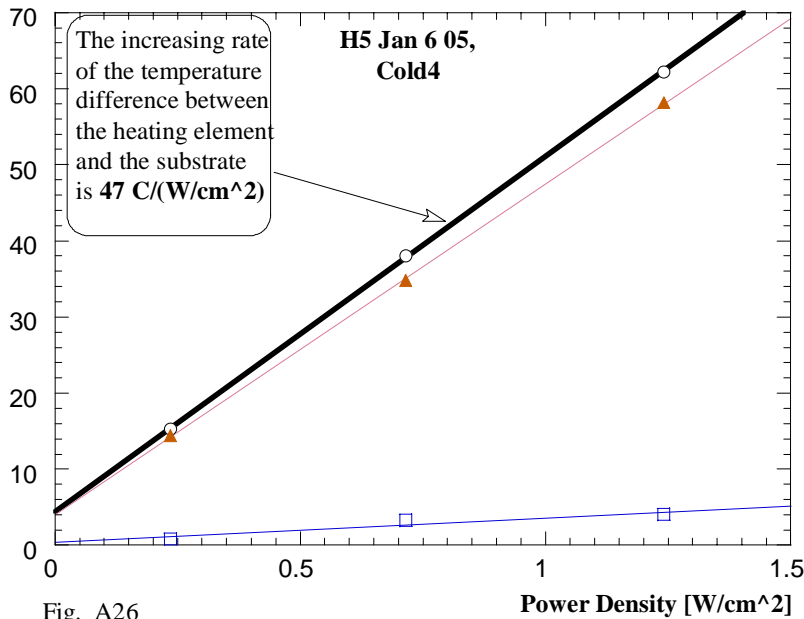


Fig. A26

—○— FeNi-(T15+T17)/2 H5 Jan6	— $y = 4.43 + 46.6x$ $R = 1$
—□— FeNi-T5 H5 Jan6	— $y = 0.423 + 3.15x$ $R = 0.953$
—▲— T5-(T15+T17)/2 H5 Jan6	— $y = 4 + 43.5x$ $R = 1$

## A6 - Heater 6

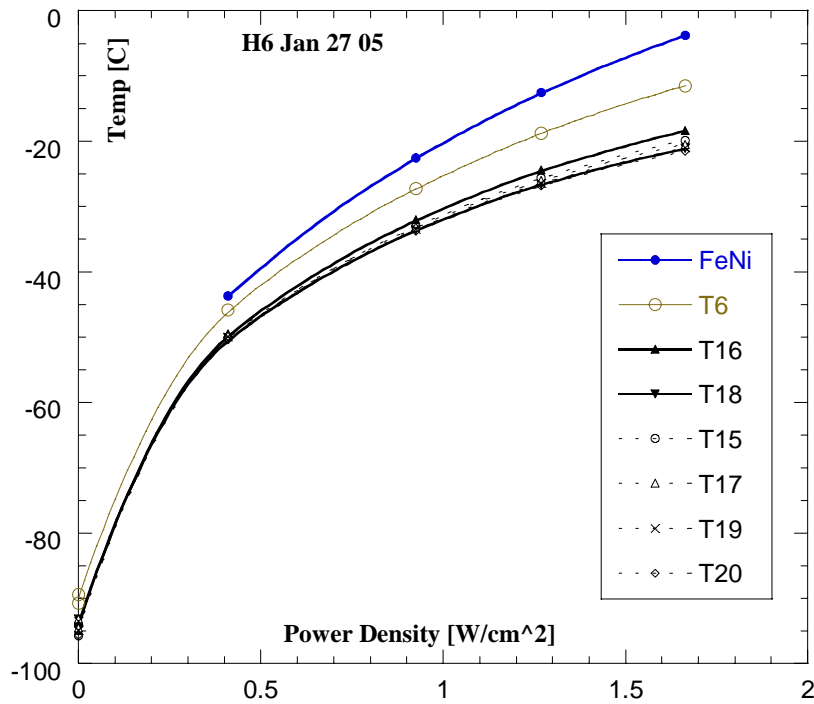


Fig. A27

FeNi is the heating element temperature

T6 is the thermometer on the top of the heater 6

T16 and T18 are the two thermometers on the TPG substrate nearby the heater 6

T15, T17, T19, T20 are the other four thermometers on the TPG substrate

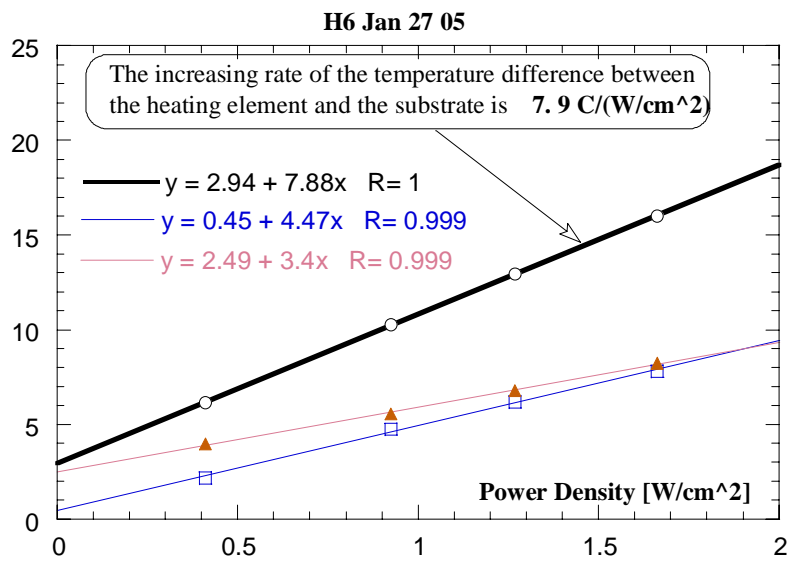


Fig. A28 The thermal contact of the heater 6 with the substrate is measured by the temperature difference between the heating element and the substrate and by the temperature difference between the top thermometer and the substrate.

—○—  $\text{NiFe} - (\text{T16} + \text{T18})/2$  is the temperature difference between the nickel-iron heating element and the substrate

—□—  $\text{NiFe} - \text{T6}$  is the temperature difference between the nickel-iron heating element and the thermometer T6 on the top of the heater

—▲—  $\text{T6} - (\text{T16} + \text{T18})/2$  is the temperature difference between the thermometer T6 on the top of the heater and the substrate

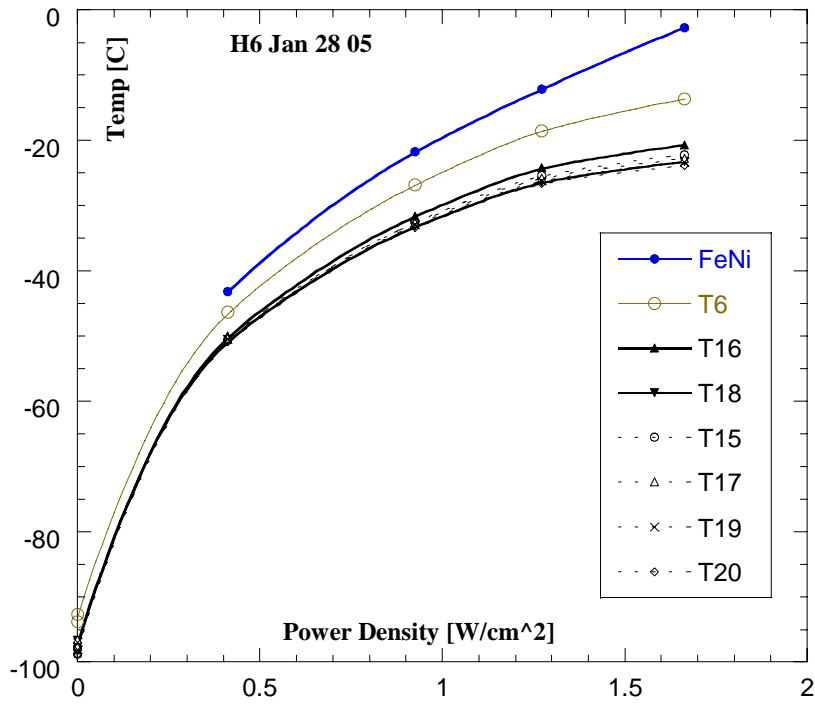


Fig. A29

FeNi is the heating element temperature

T6 is the thermometer on the top of the heater 6

T16 and T18 are the two thermometers on the TPG substrate nearby the heater 6

T15, T17, T19, T20 are the other four thermometers on the TPG substrate

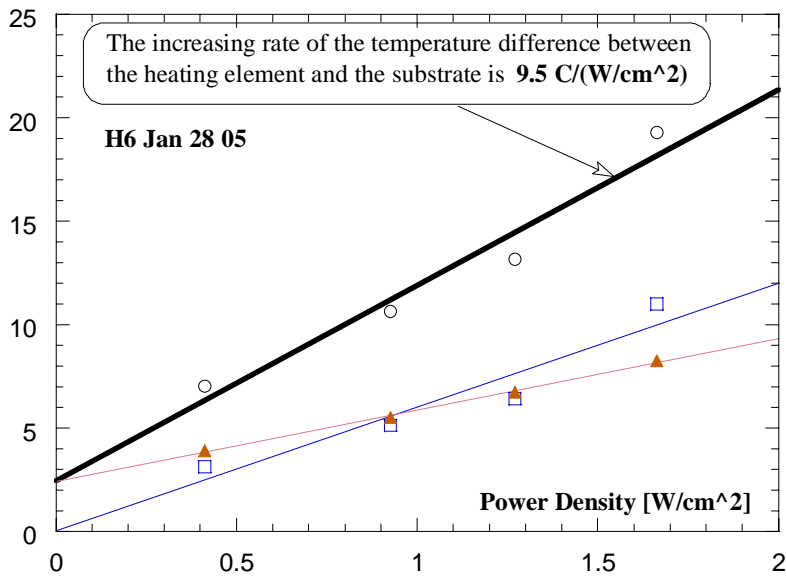


Fig. A30

—○— FeNi-(T16+T18)/2 HTR6 Jan28	— $y = 2.44 + 9.46x$ $R = 0.976$
—□— FeNi-T6 HTR6 Jan28	— $y = 0.0255 + 5.99x$ $R = 0.952$
—▲— T6-(T16+T18)/2 HTR6 Jan28	— $y = 2.41 + 3.47x$ $R = 0.999$

## A7 - Heater 7

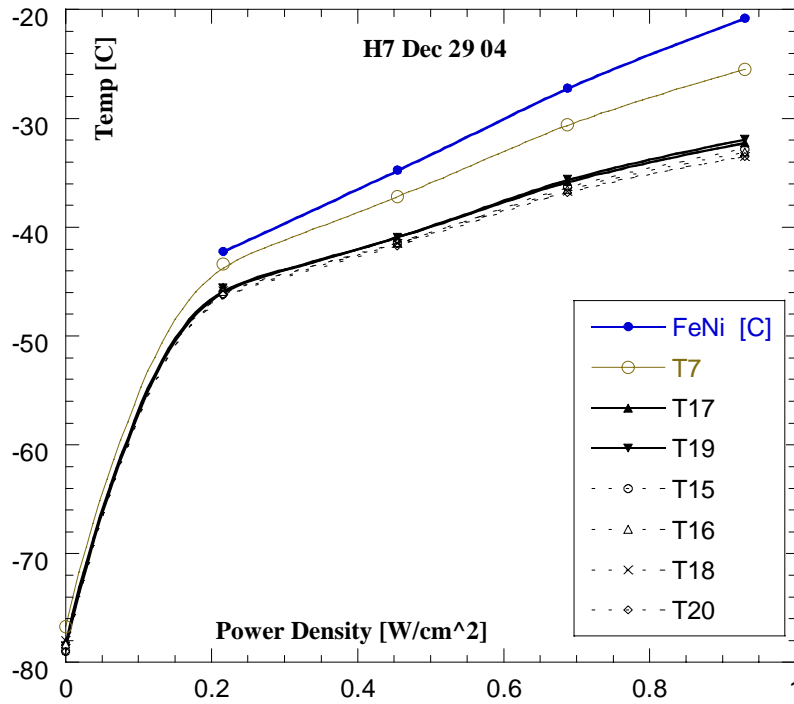


Fig. A31

FeNi is the heating element temperature

T7 is the thermometer on the top of the heater 7

T17 and T19 are the two thermometers on the TPG substrate nearby the heater 6

T15, T16, T18, T20 are the other four thermometers on the TPG substrate

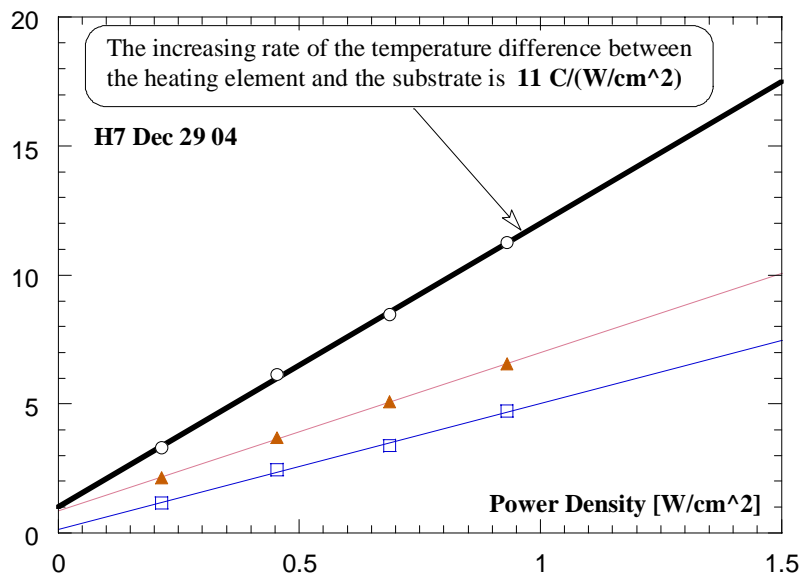


Fig. A32

—○— FeNi-(T17+T19)/2 HTR7 Dec29

—□— FeNi-T7 HTR7 Dec29

—▲— T7-(T17+T19)/2 HTR7 Dec29

— y = 0.999 + 11x R= 1

— y = 0.136 + 4.87x R= 0.998

— y = 0.863 + 6.14x R= 1

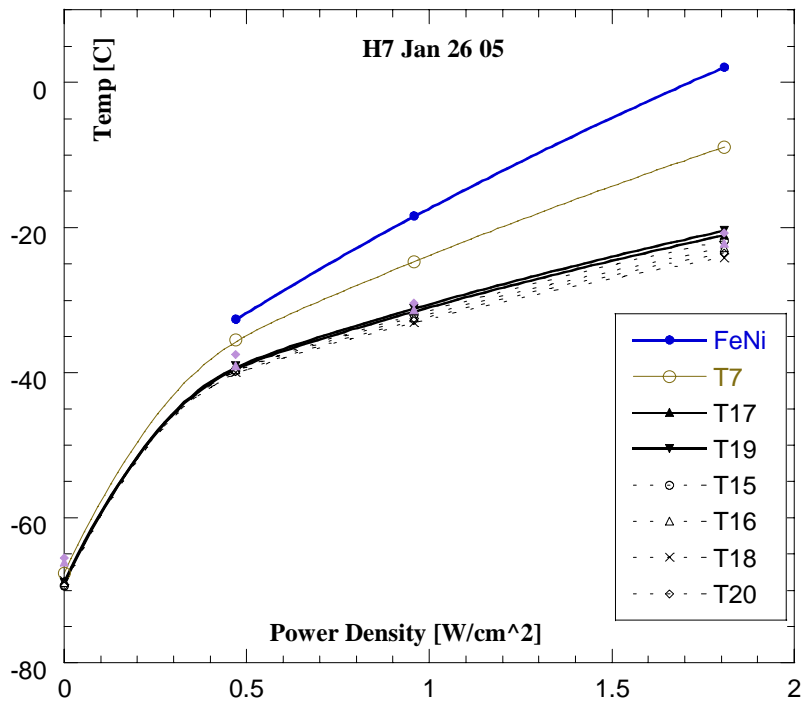


Fig. A33

FeNi is the heating element temperature

T7 is the thermometer on the top of the heater 7

T17 and T19 are the two thermometers on the TPG substrate nearby the heater 6

T15, T16, T18, T20 are the other four thermometers on the TPG substrate

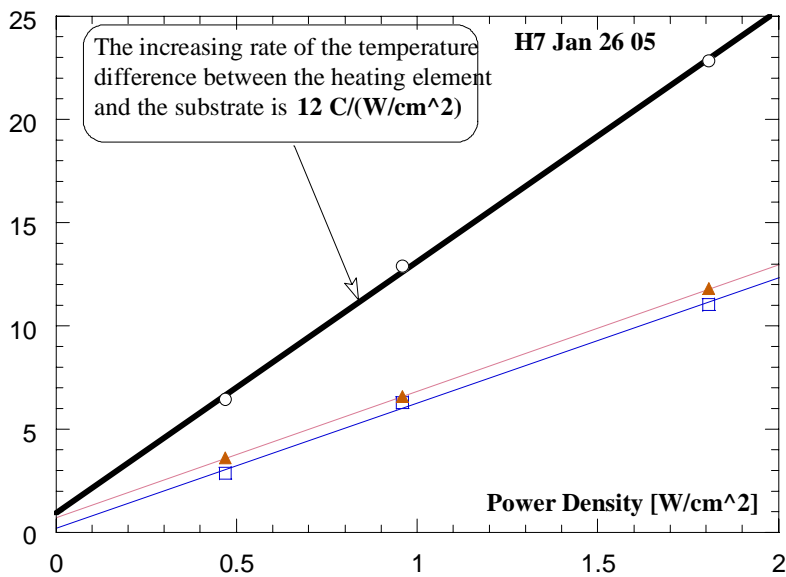


Fig. A34

—○— FeNi-(T17+T19)/2 HTR7 Jan26	— $y = 0.928 + 12.2x$ $R = 0.999$
—□— FeNi-T7 HTR7 Jan26	— $y = 0.205 + 6.05x$ $R = 0.998$
—▲— T7-(T17+T19)/2 HTR7 Jan26	— $y = 0.722 + 6.13x$ $R = 1$

## A8 - Heater 8

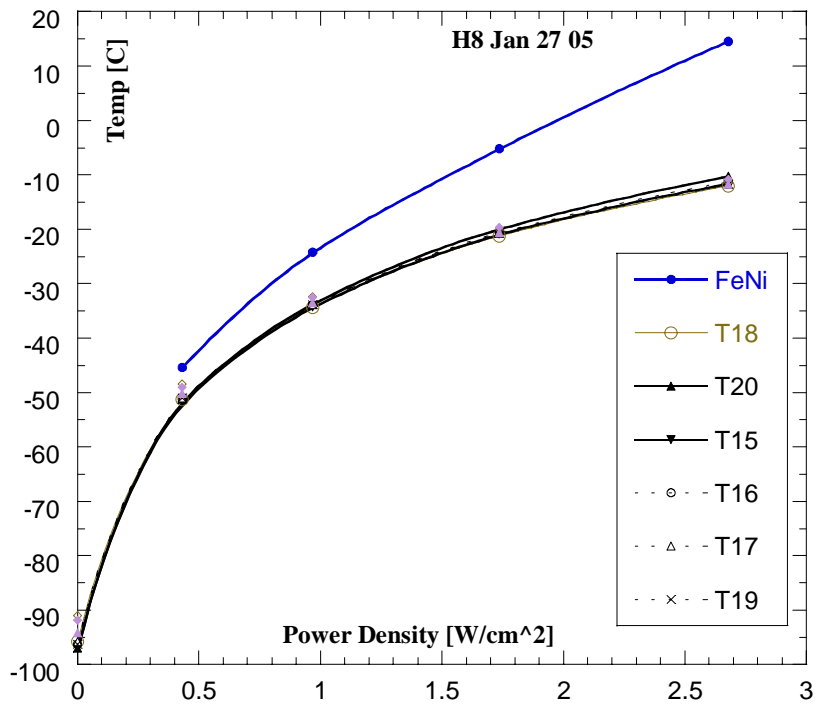


Fig. A35

FeNi is the heating element temperatures

The thermometer T8, on the top of the heater 8, does not work

T18 and T20 are the two thermometers on the TPG substrate nearby the heater 8

T15, T16, T17, T19 are the other four thermometers on the TPG substrate

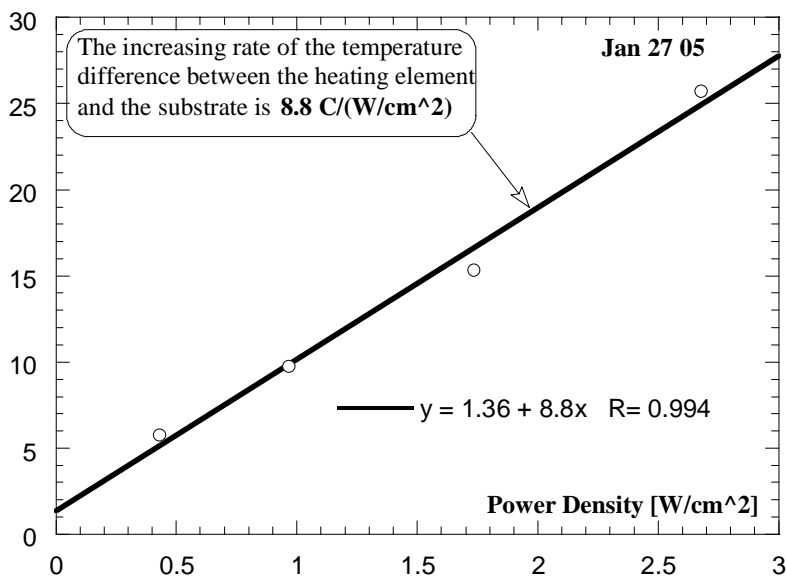


Fig. A36 Thermal contact of the heater 7 with the TPG substrate. The thermometer T8 on the top of this heater does not work.

—○— FeNi-(T18+T20)/2 H8 Jan27

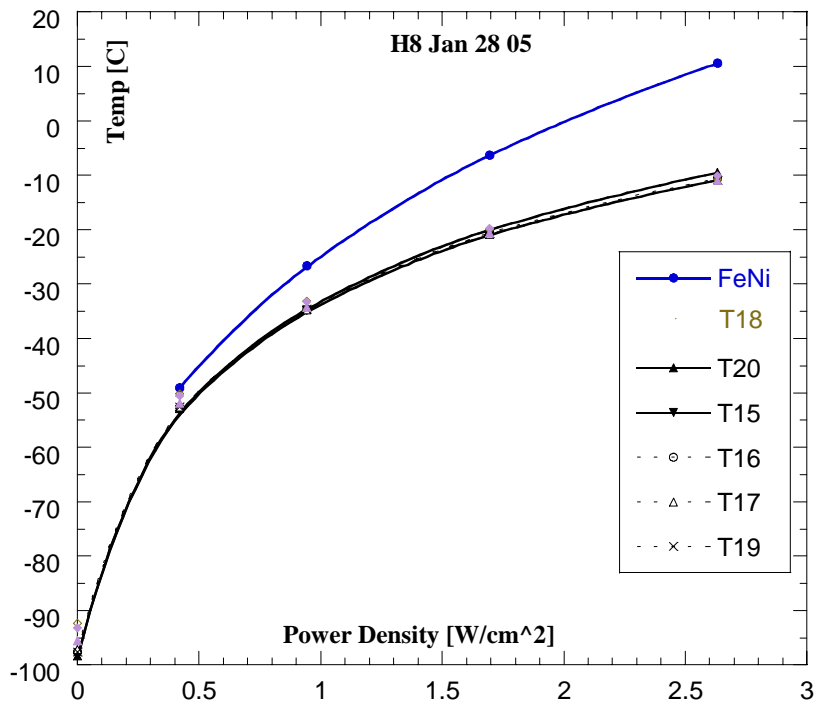


Fig. A37

FeNi is the heating element temperature

The thermometer T8, on the top of the heater 8, does not work

T18 and T20 are the two thermometers on the TPG substrate nearby the heater 8

T15, T16, T17, T19 are the other four thermometers on the TPG substrate

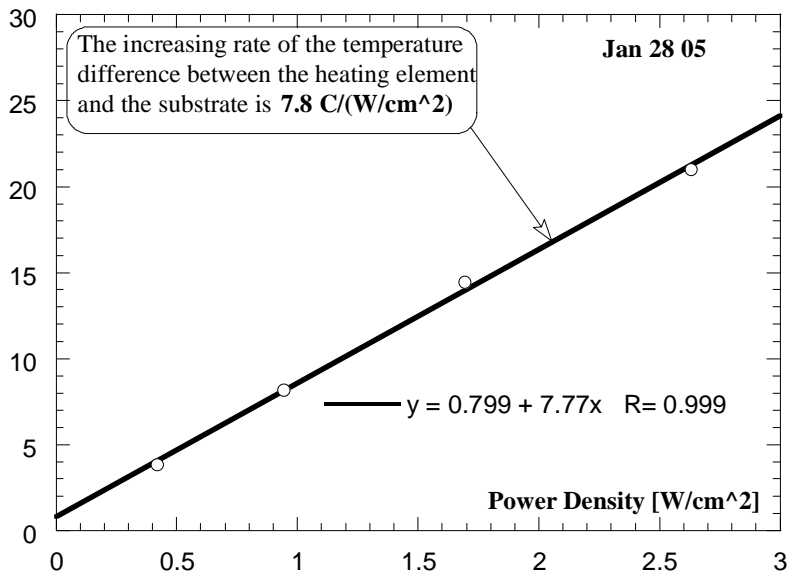


Fig. A38 Thermal contact of the heater 7 with the TPG substrate. The thermometer T8 on the top of this heater does not work.

—○— FeNi-(T18+T20)/2 H8 Jan28

## Appendix B: Second Test Measurements

### B1 - Heater 1

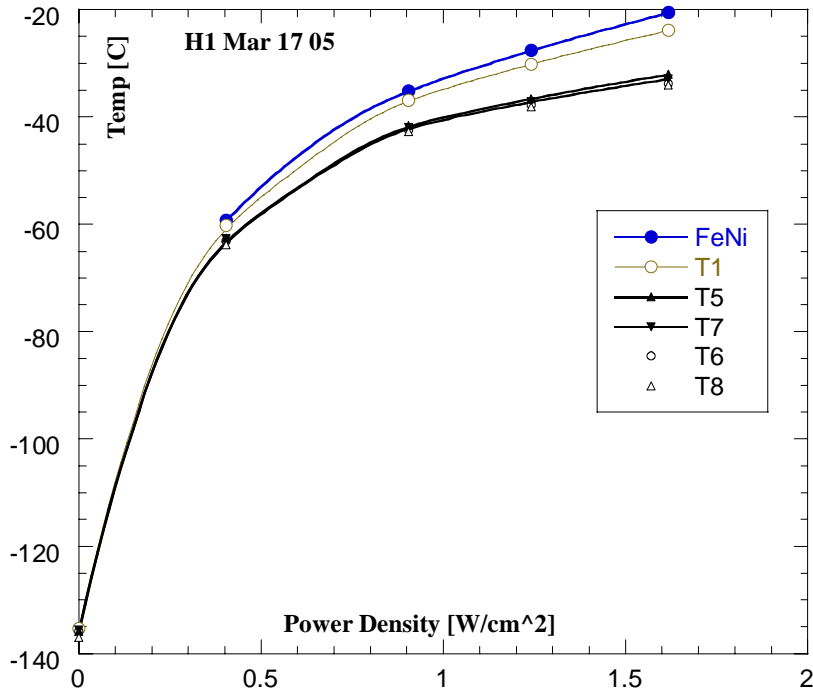


Fig. B1

FeNi is the heating element temperature

T1 is the thermometer on the top of the heater 1

T5 and T7 are the two thermometers on the TPG substrate nearby the heater 1

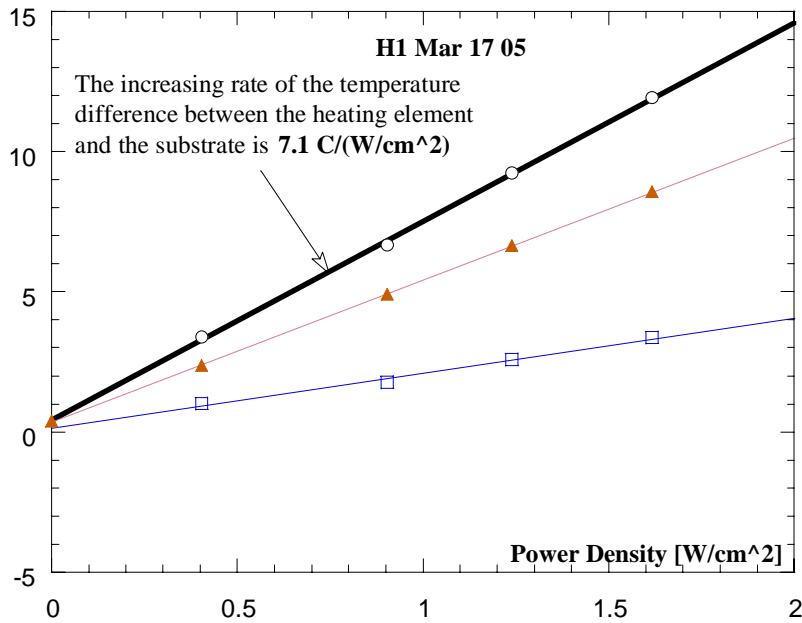


Fig. B2

—○— FeNi-(T5+T7)/2 H1 Mar17 05

—□— FeNi-T1 H1 Mar17 05

—▲— T1-(T5+T7)/2 H1 Mar17 05

— y = 0.436 + 7.08x R= 1

— y = 0.142 + 1.96x R= 0.995

— y = 0.359 + 5.06x R= 1

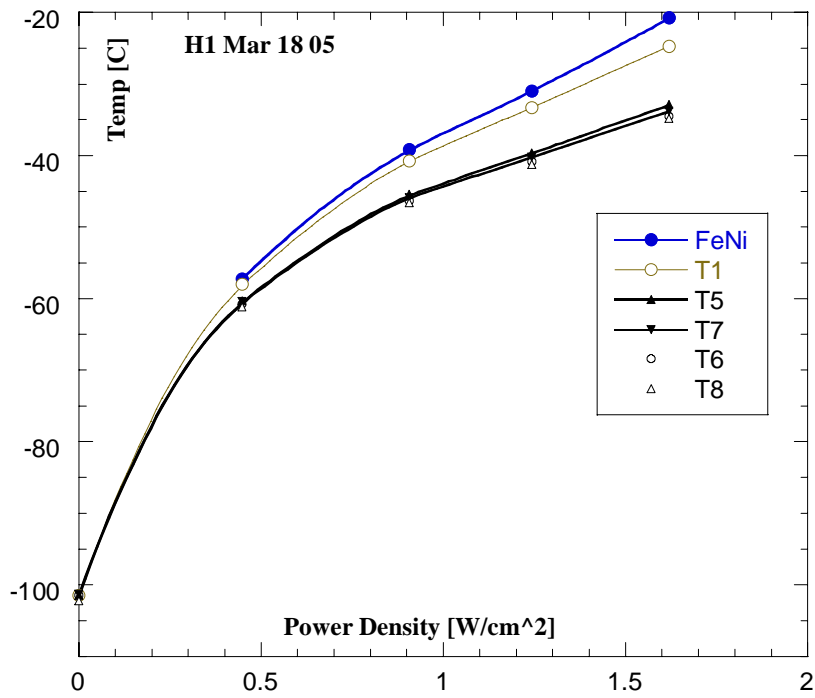


Fig. B3

FeNi is the heating element temperature

T1 is the thermometer on the top of the heater 1

T5 and T7 are the two thermometers on the TPG substrate nearby the heater 1

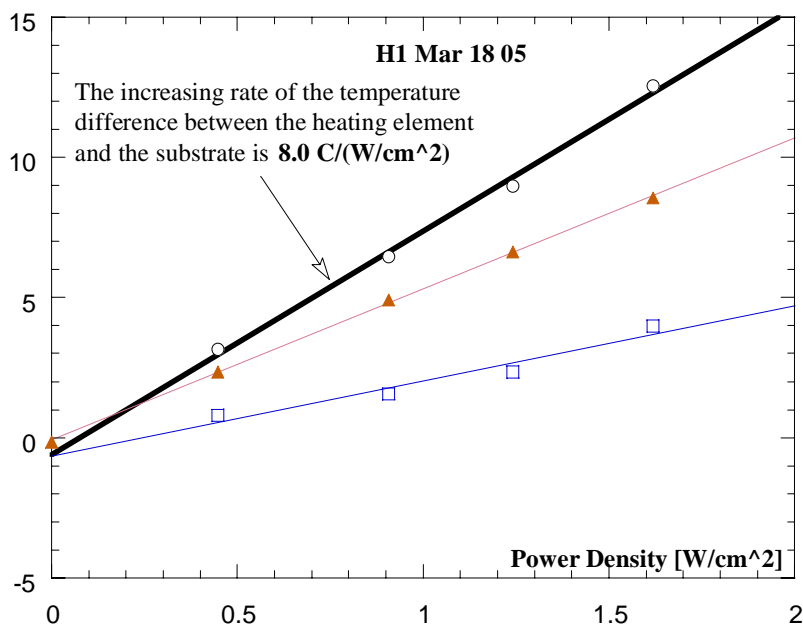


Fig. B4

—○— FeNi-(T5+T7)/2 H1 Mar18 05	— y = -0.603 + 7.96x R= 0.998
—□— FeNi-T1 H1 Mar18 05	— y = -0.641 + 2.67x R= 0.972
—▲— T1-(T5+T7)/2 H1 Mar18 05	— y = -0.0849 + 5.39x R= 1

## B2 - Heater 2

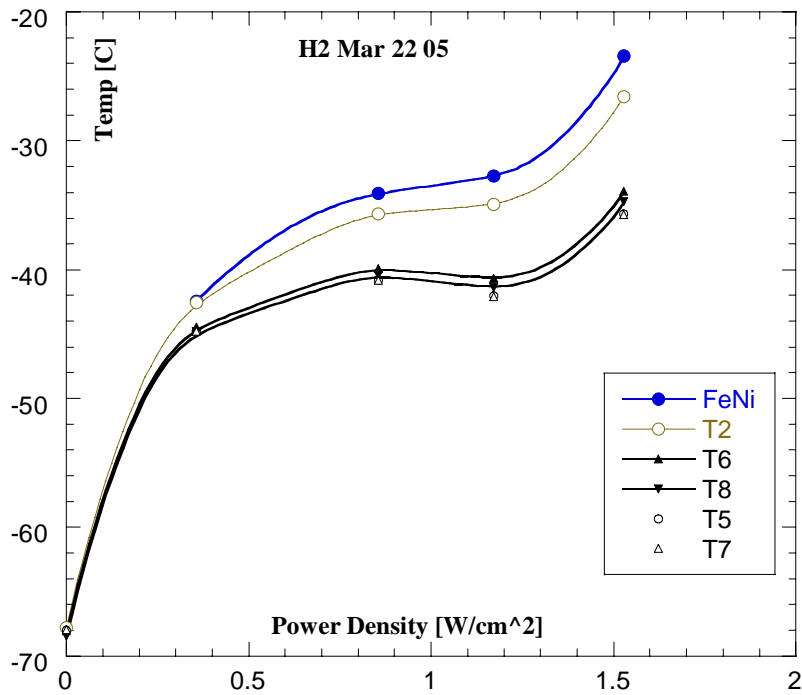


Fig. B5

FeNi is the heating element temperature

T2 is the thermometer on the top of the heater 2

T6 and T8 are the two thermometers on the TPG substrate nearby the heater 2

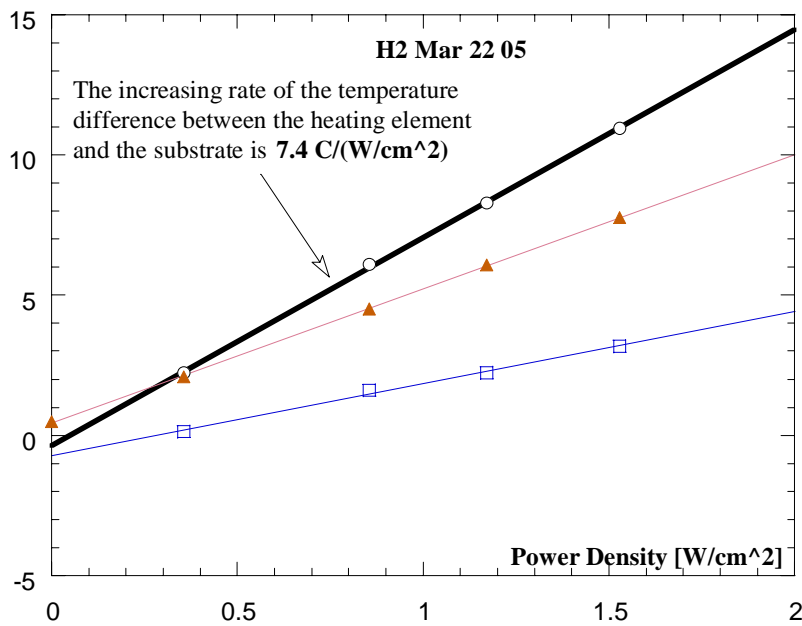


Fig. B6

—○— FeNi-(T6+T8)/2 H2 Mar22 05	— y = -0.356 + 7.41x R= 1
—□— FeNi-T2 H2 Mar22 05	— y = -0.718 + 2.56x R= 0.998
—▲— T2-(T6+T8)/2 H2 Mar22 05	— y = 0.442 + 4.78x R= 1

### B3 - Heater 3

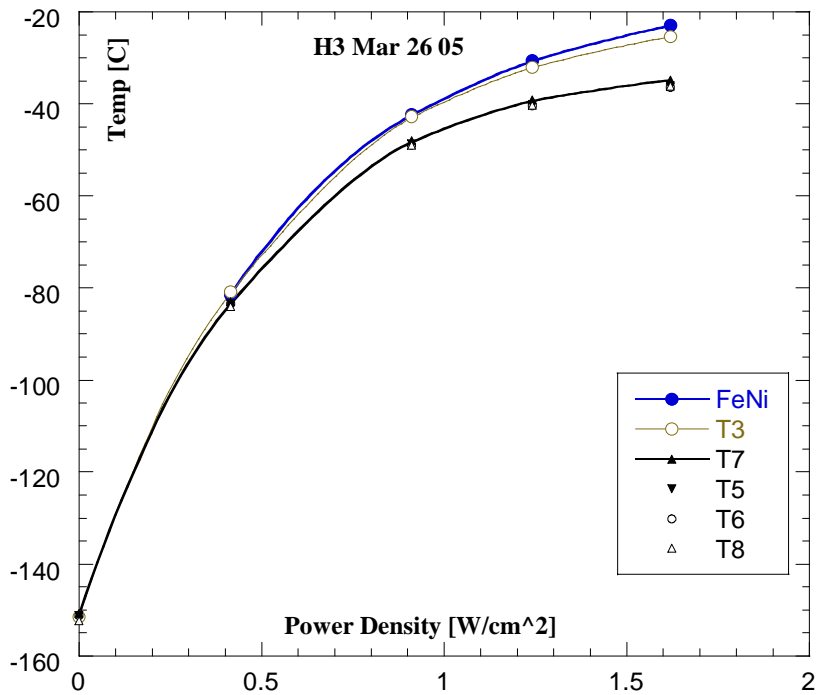


Fig. B7

FeNi is the heating element temperature

T3 is the thermometer on the top of the heater 3

T7 is the thermometers on the TPG substrate near the heater 3

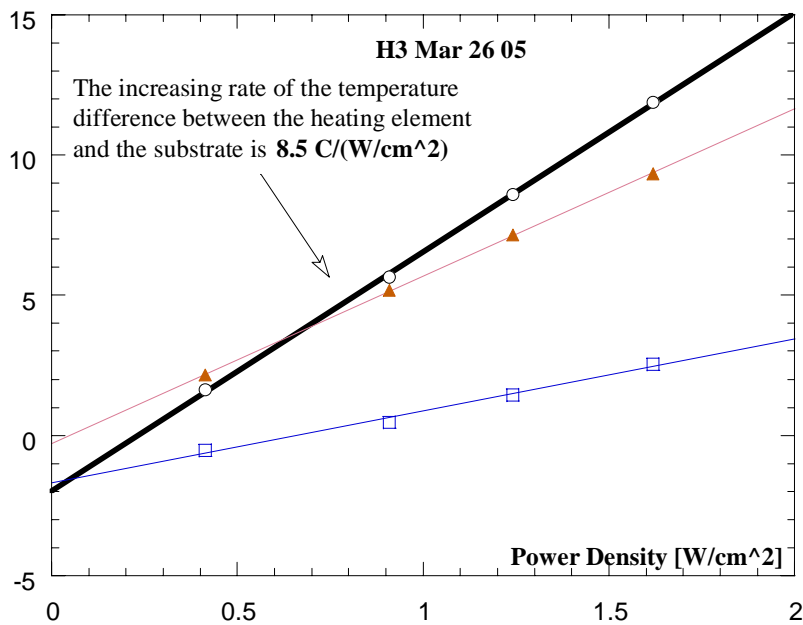


Fig. B8

—○— FeNi-T7 H3 Mar26 05

—□— FeNi-T3 H2 Mar26 05

—▲— T3-T7 H3 Mar26 05

$$y = -1.98 + 8.52x \quad R = 1$$

$$y = -1.69 + 2.56x \quad R = 0.995$$

$$y = -0.288 + 5.97x \quad R = 1$$

## B4 - Heater 4

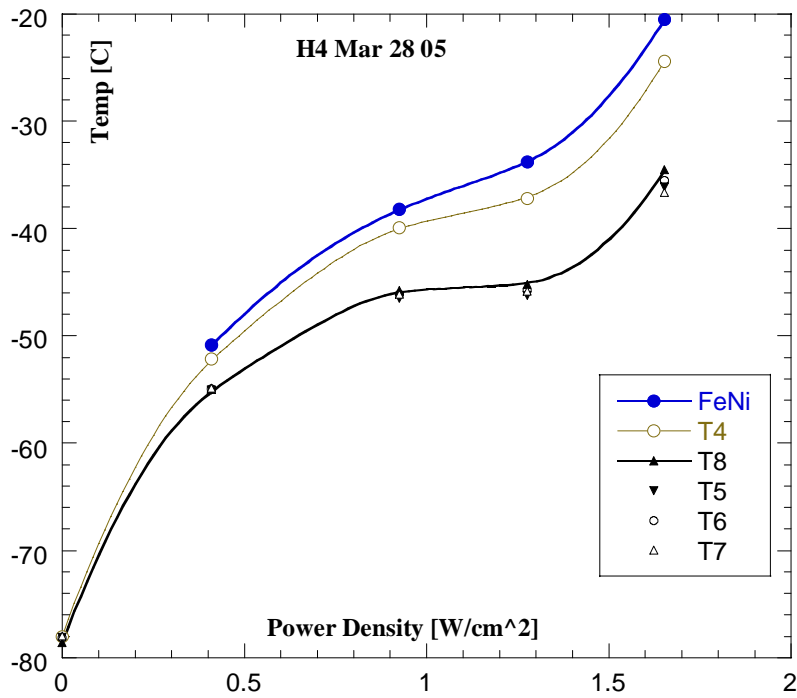


Fig. B9

FeNi is the heating element temperature

T4 is the thermometer on the top of the heater 4

T8 is the thermometers on the TPG substrate near the heater 4

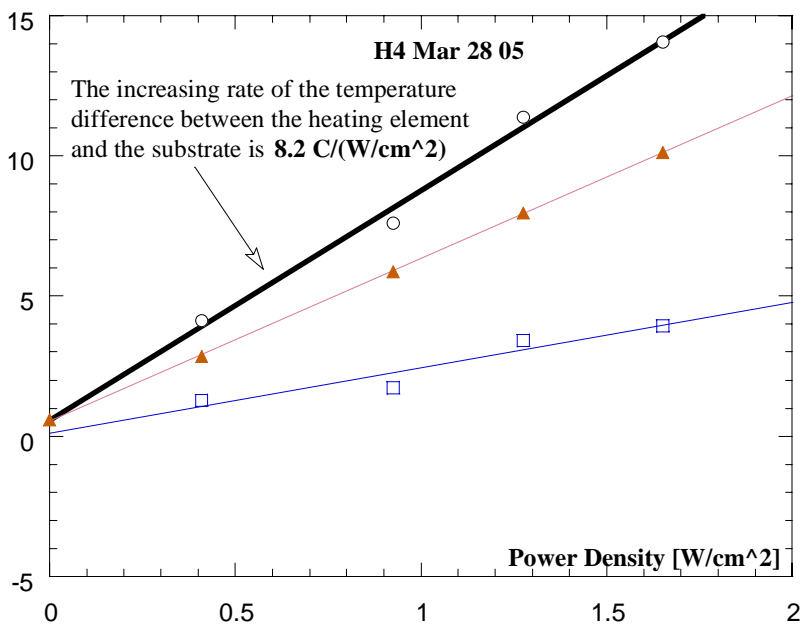


Fig. B10

—○— FeNi-T8 H4 Mar28 05

—□— FeNi-T4 H4 Mar28 05

—▲— T4-T8 H4 Mar28 05

— y = 0.562 + 8.19x R= 0.996

— y = 0.111 + 2.33x R= 0.955

— y = 0.537 + 5.8x R= 1